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SUNBEAMS FROM SPACE MIRRORS IN DAWN-DUSK POLAR ORBIT FEEDING SOLAR FIELDS ON THE GROUND FOR LOW COST ELECTRICITY

Lewis M. Fraas
JX Crystals Inc, USA, lfraas@jxcrystals.com

A Space Power Satellite capable of providing solar electric power economically for 24 hours per day has been a dream for decades. However, the SPS concept is very complex since it assumes multiple energy conversion steps and includes specially constructed ground microwave receiver stations. The 5 km by 15 km Integrated Symmetric Concentrator SPS concept employs light weight mirrors in a GEO orbit. Herein, it is proposed to use a constellation of 10 km diameter mirror arrays in a much lower sun synchronous orbit at an altitude of 1000 km deflecting sunbeams down to terrestrial solar power fields at dawn and dusk. The key is that larger and larger terrestrial solar fields, photovoltaic or trough concentrated solar power, are already being built all around the world. Mirrors deflecting sunbeams down to earth is a much simpler concept. A surprising convergence of two technologies under development is now possible, i.e. lower cost access to space and the ongoing construction of numerous larger solar power fields. The novelty here is the idea of a constellation of mirrors in a sun-synchronous dawn/dusk orbit in combination with future multiple 5-GW solar farms distributed around the world. In this scenario, the projected payback time for the mirror constellation given the additional revenues from the multiple solar fields is approximately 2 years. The key to the attractive economics for this concept is that the mirror constellation is used continuously over a 24 hour period by multiple terrestrial fields as each field comes into view at dawn or dusk. However, while this idea is very intriguing, the magnitude of its implementation is daunting. Nevertheless, the idea is intriguing enough to proceed with an initial design for the required mirror satellites. A mirror satellite design is presented here. It builds from mirror technology for solar sails as well as technology developed for the International Space Station. It appears that the technology is available to implement this mirror satellite design and at least go to a detailed design and test stage. Given all of the above, there is still another non-technical difference between this dawn dusk space mirror concept and the initial SPS concept and that difference is in perspective. The dawn dusk space mirror concept requires a global perspective and international cooperation whereas the SPS concept is based on a traditional national perspective. In this regard, the International Space Station does provide hope for future international cooperation.

I. INTRODUCTION

The Solar Power Satellite ("SPS") concept, a proposed method of generating solar electricity for 24 hours per day in space and transmitting it to earth to solve the energy needs of the Earth with a clean, zero-emissions energy source has been a dream since the 1970s [1]. The proposals to do this mostly focus on microwave transmission as the means to deliver the power to Earth. Due to the fundamental physics of diffraction-limited beam spread, such transmission requires apertures and receivers that are on the scale of kilometres, and hence require exceptionally large systems in space. For example, a NASA design concept, the Integrated Symmetrical Concentrator Solar Power Satellite (ISC SPS) is shown in Fig. 1. It is 5 x 15 km in size, and requires a ground station 8 km in diameter [2]. The size, mass, and power levels of this orbital system makes the proposed SPS extremely expensive.

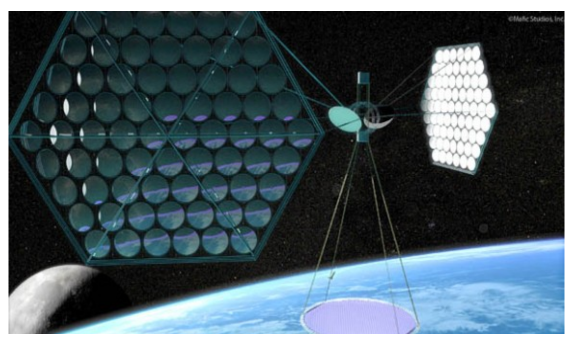


Fig. 1: This NASA proposed Integrated Symmetric Concentrating Space Power Satellite uses large mirror arrays but is very complex, expensive, and in GEO [2].

A concept proposed in 2012, the MiraSolar array constellation [3, 4], avoids this problem. As proposed by Ehricke [5], mirrors in orbit can be used to reflect sunlight to the Earth. This solution minimizes the size and mass of the space element by placing most of the complex power generation infrastructure on the ground, and using only lightweight mirror elements in space. The concept allows the ability to "ramp up" power by using a ground infrastructure that is already being built. The concept is to put a large mirror array in low Earth orbit (LEO) at 1000 km, rather than the geosynchronous orbit proposed for earlier concepts, allowing a smaller and far simpler configuration. The multiple energy conversion steps in space are eliminated. The ground stations are conventional solar fields (PV or trough CSP) already being built. Thus, rather than competing with ground solar technologies, this concept is synergistic: it works with solar ground stations, not against them, and hence it can leverage a billion-plus dollar ground technology infrastructure that is already being developed.

Furthermore, while conventional concepts for SPS would require array assembly in space, the mirror elements proposed here are self deploying and can be launched by today's launch vehicles.

This concept is cross cutting between NASA Space and terrestrial alternative energy developments. As shown in Fig. 2, this concept represents a convergence of two ongoing revolutions: the reduction of the cost of access to space, and a continuing remarkable growth in terrestrial solar electric power resulting in a potential cost savings of up to a factor of 10 relative to the ISC SPS concept [3, 4].

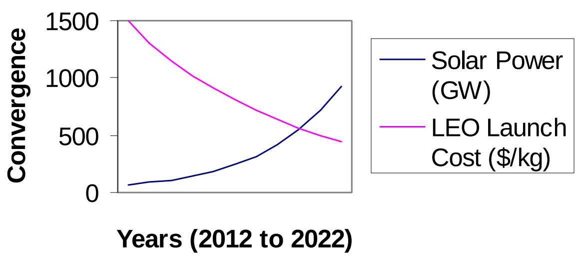


Fig. 2: Space & Terrestrial Cost Convergence.

II. MIRROR ARRAY CONSTELLATION CONCEPT

The mirror-array concept places mirrors in "sun synchronous" orbit, in which orbital perturbations rotate the orbital plane by 360/365 of a degree per day, thus keeping the orbit at the same orientation to the sun, and hence passing over a given ground location at the same (solar) time each day. At an orbital altitude of 1000 km, a sun-synchronous orbit is achieved at an inclination of 99.5° (*i.e.*, 9.5° inclined from polar) [6]. The orbital plane chosen is a "dawn/dusk" orbit, which nearly follows the Earth's terminator, and thus passing overhead once in the morning and once in the evening.

A mirror satellite constellation in such a dawn dusk orbit could harvest solar energy and reflect sunlight down to Earth as shown in Fig. 3 and Fig. 4. Sunlight reflected from these mirror satellites is directed at terrestrial solar farms. In 10 years, there will be many solar farms generating electricity around the world.

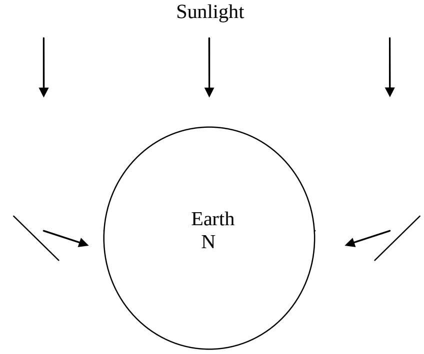


Fig. 3: Mirror satellites can deflect sunlight to earth.

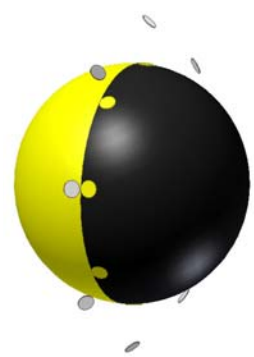


Fig. 4: A constellation of mirror satellites deflects sunbeams to earth solar farms to generate electricity in the evening. Here the mirror satellites are very much exaggerated in size.

This scenario has been described previously [3, 4] with an 18-mirror array satellite constellation in a dawn/dusk orbit. Because of the sun's angular diameter, the reflected spot size at the surface would be approximately 10 km in diameter [3] and the solar farm could then produce 5.5 GW of electricity. The specific scenario described assumed a constellation of 18 mirror-array satellites and 40 terrestrial solar farms generating 5.5 GW each. With these assumptions, the result was that assuming the mirror masses associated with the NASA-sponsored L'Garde solar sail (mirror), the launch cost assumed by NASA for a future Space Power Satellite, and solar electricity cost of 10 cents per kWh, the payback time for this mirror satellite constellation could be as low as 0.7 years. However, this payback time will depend on actual launch costs.

The altitude for the mirror system has not been optimized. It would most likely be chosen so that the mirror makes an integral number of orbits in a 24-hour period, and thus the ground track of the orbit repeats exactly each day. Likely orbits would be either 900 km altitude, for 14 orbits per day, 1250 km for 13 per day, or 600 km for 15 orbits per day. A 1000-km orbital altitude, intermediate between these values, is used for representative calculations here.

Given this promising economics for an 18-mirror array satellite constellation, it was then reasoned that three 18-satellite constellations spaced in longitude as shown in Fig. 5 would be equally economical.

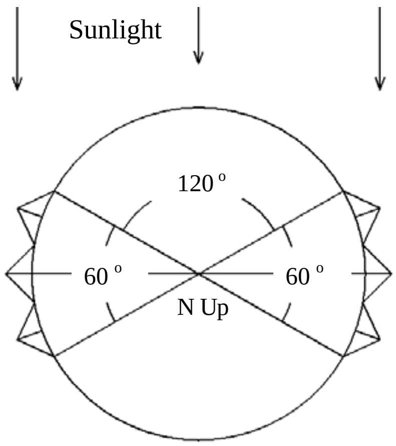


Fig. 5: 18 mirror satellite constellations in 3 orbital planes spaced in longitude with accessible angular ranges shown.

The potential impact of three longitudinally-spaced planes of mirror satellites on the hours of energy production at the solar farms is shown in Fig. 6. As seen, at a well-chosen favourable site, the mirror satellites can add 3 hours of electrical production in the morning and 3 hours in the evening, extending the solar electrical production from 8 hours to 14 and thus increasing the capacity factor from 33% to 58%.

This electrical generation profile has significant advantages over a baseline SPS design generating constant power for 24 hours per day. As pointed out by Landis [7], a dawn/dusk power generation fills in ground solar generation at peak times, but does not generate power during off-peak hours centred around midnight, when very little electrical power is needed (and hence selling prices for electrical power are low).

The size of each of the mirror array satellites in this concept [3, 4], gives one pause. Even assuming ideal flatness, to produce 1-sun intensity the mirror projected area for each of the 18 (or 54) satellites in the constellation must equal the area of the 10-km diameter terrestrial solar farm. However, note that the mirror area is comparable to the size of the mirror on the proposed ISC design for a Power Satellite in GEO, 5 km by 15 km [2] and the ISC ground station would only produce 1.5 GW rather than 5 GW.

Fig. 5 gives some perspective on this mirror array size. Relative to the size of the Earth, these mirror array satellites are really no larger than pin points. Furthermore, Fig. 7 gives a perspective of the size of this area relative to the size of the contamination zone around the 5-GW Fukushima nuclear power plant.

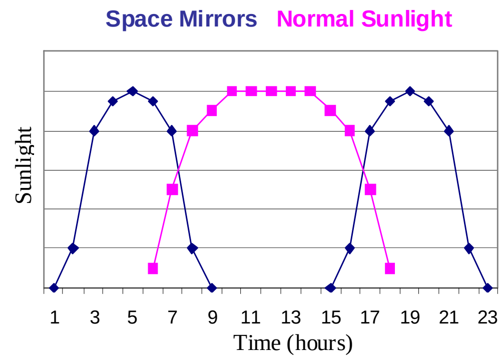


Fig. 6: The mirror satellite constellation can extend the hours of solar electricity production from 8 to 14 by adding 3 more hours in the morning and 3 more hours in the evening.

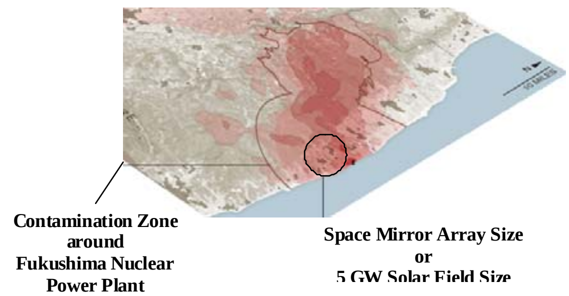


Fig. 7: Space Mirror Size Relative to Fukushima Nuclear Contamination Zone

Finally, Figure 8 provides still another perspective on the sunbeam from space mirror concept. Notice that the sunbeam is just directed at a solar field already dedicated to solar electric power generation.

Figure 8: A solar field can potentially generate power in the evening as well as during the day.

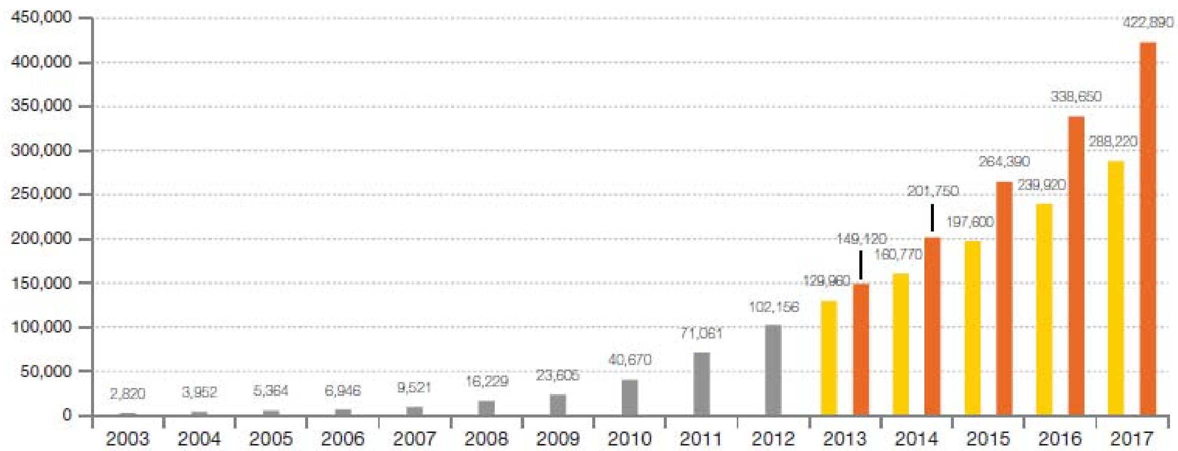


Figure 9: European Photovoltaic Industry Association Global Market Outlook for Photovoltaics 2013-2017. Cumulative installed PV [8].

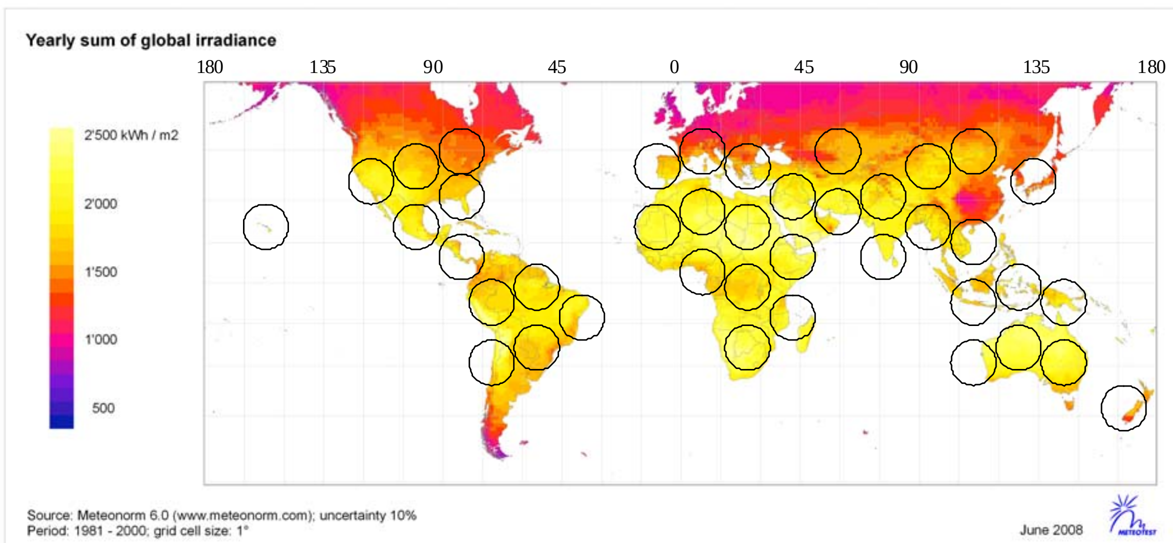


Figure 10: Hypothetical 5.5 GW solar power installation global map for 2022. The circles note when a mirror array satellite is in range for a given solar power field. The key to the attractive economics for this concept is that the mirror constellation is used continuously over a 24 hour period by multiple terrestrial fields as each field comes into view at dawn or dusk.

III. GROUND SOLAR FARMS AROUND THE WORLD

The second element key for the economics for this sunbeams-from-space concept is the requirement for multiple solar farms distributed around the world. Is this a credible assumption for 10 years from now? Figure 9 shows the cumulative growth of solar PV from 2003 to 2012 along with a future growth projection out to 2017 [8]. In 2012, the total worldwide solar PV installed capacity reached 102 GW. Assuming a growth rate of 30% per year, one can project $102x(1.3)^5 = 378$ GW by 2017 in reasonable agreement with the figure 9 projection and then $102x(1.3)^{10} = 1400$ GW by 2022. The economic argument [3, 4] for this MiraSolar constellation assumes forty 5.5 GW ground solar power stations for a total installed capacity of 220 GW. This 220 GW power level is small compared with the projected 1400 GW total. Figure 10 shows a hypothetical global distribution for these 40 ground stations. Given the same launch cost assumption made by NASA for the ISC SPS of $400 per kg, the projected mirror constellation payback time came out to be 0.7 years.

While there are many uncertainties in predicting the future, nevertheless, this concept is still very exciting. For example, if one were to assume forty 5.5 GW ground stations and a launch cost of $1100 per kg, the payback time would change to just 2 years. Alternately, with the $400 per kg launch cost and forty 2 GW ground stations, the payback time is still just 2 years.

IV. WHAT ABOUT GLOBAL WARMING

With mirrors in space deflecting sunbeams down to earth, is there a potential problem of global warming? The answer is no, not in the usual context of global warming. Remember that when one discusses global warming, the concern is with increased levels of CO_2 and the permanent impact of that on the earth's cooling rate. The earth's temperature is controlled by a balance between the energy input from the sun and the cooling of the earth by infrared radiation into space. Increases in the CO_2 in the atmosphere produce a green house effect which reduces the infrared energy radiated into space for cooling. Permanent rises in CO_2 produce a permanent temperature rise. Table I summarizes the global warming effects from additional energy production versus the CO_2 green house effect.

Table I: The temperature rise from burning hydrocarbon fuel is permanent.

Add 220 GW New Electric Power	Delta T New Energy	Delta T Shut Down No Energy	Delta T From CO_2 (over 1st 20 yrs)
With Nuclear (24 hours/day)	**0.002 °C**	**0**	**0**
Space Mirrors (6 hours/day)	**0.0018 °C**	**0**	**0**
From Natural Gas (24 hrs/day)	**0.0015 °C**	**0**	**Add 0.0032 °C Permanent***
From Coal (24 hrs/day)	**0.002 °C**	**0**	**Add 0.0057 °C Permanent***

* These numbers double in 2nd 20 years.

When one produces electrical energy by using sunlight or by a nuclear reaction in a nuclear power plant, the additional energy produced adds energy to the daily sunlight energy input increasing the earth's temperature very slightly. In the present case where an additional 220 GW of electrical power is produced via sunlight from space mirrors equivalent to the power from 40 nuclear power plants, the earth's temperature rise can be calculated to be 0.0018 C. However, if one chooses not to produce that 220 GW of electrical power by redirecting the sun beams away from the earth, the temperature rise is zero. There is no additional global warming. Meanwhile, if one chooses to produce this same amount of electrical power by burning natural gas for the next 20 years, the earth's temperature rise can be calculated to be 0.0032 C and if burning coal, the temperature rise would be 0.0057 C or 3.2 times higher. The difference is that the temperature rise from burning hydrocarbon fuels is permanent and accumulates with time. Finally, note that all of these effects associated with 220 GW of additional electric power are very small. However, in reality today, mankind consumes much more than just 220 GW of electricity. So the effects of burning fossil fuels are much larger and the benefits of not burning fossil fuels can also be much larger (See Table I and Appendix).

V. MIRROR SATELLITE DESIGN

In a realistic system, the mirror array satellites can be composed of a larger number of smaller mirror satellites. Our thesis is that if one mirror satellite can be designed and demonstrated, then it can be replicated as needed for a constellation. What might these smaller mirror satellites look like? In a folded form, they will have to fit in the fairing of a launch vehicle, and each one will need to have attitude control that will allow the mirror sunbeam to be directed at a particular solar farm as the mirror satellite passes overhead. Figs. 11 to 14 show a design concept.

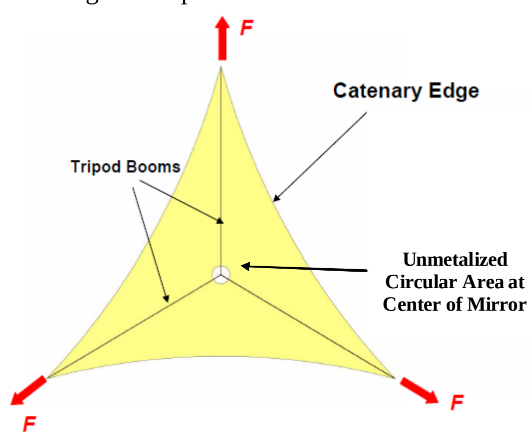


Fig. 11: Example deployable thin-film mirror satellite with edge dimension 307 m.

The satellite consists of a triangular mirror with an edge dimension of 307 m. The triangular configuration was chosen because it can be supported with three booms with springs at the ends of the boom at three points then defining a plane. The springs stretch the 2.5 micron thick mirror membranes flat. The edge dimension was chosen so that the mirror can fold up to fit in today's launch vehicles. The booms are supported by a centre body containing attitude control and communication systems for the satellite.

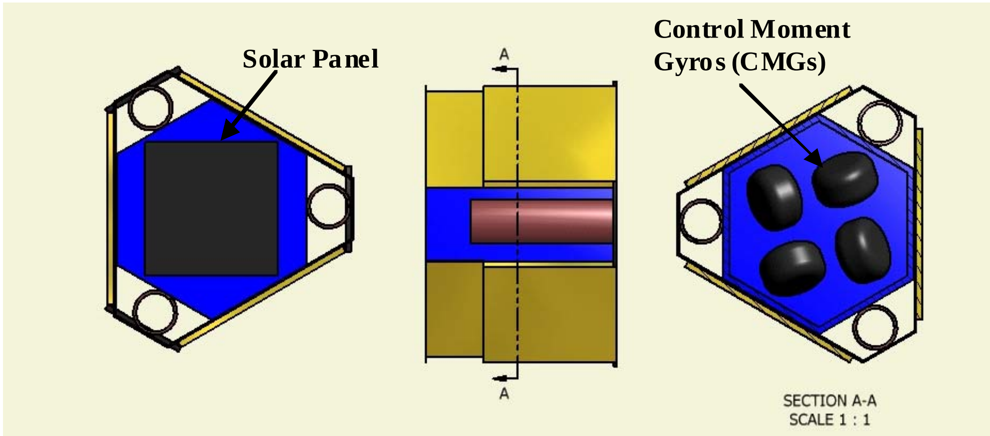


Fig. 12: Mirror satellite in stowed configuration (4.6 m x 3 m). Note top solar panel for power on left and CMGs in body on right.

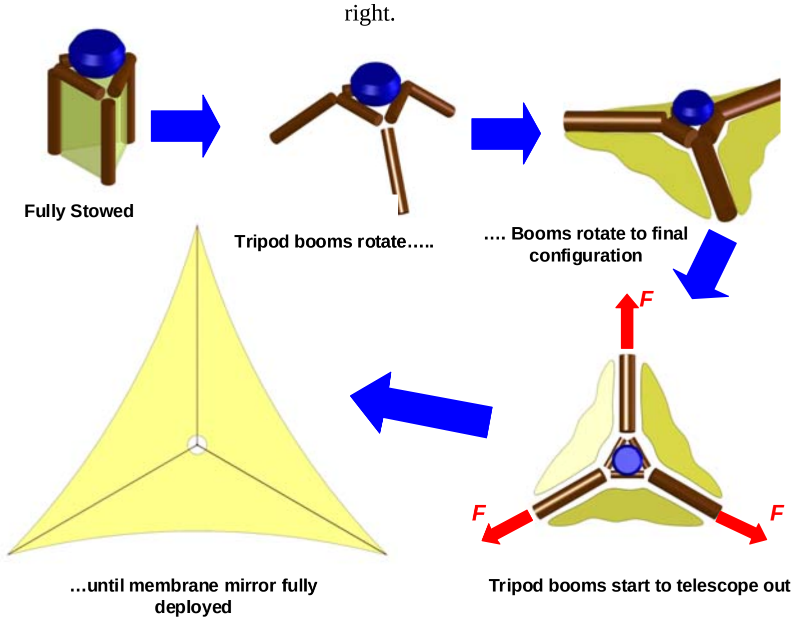
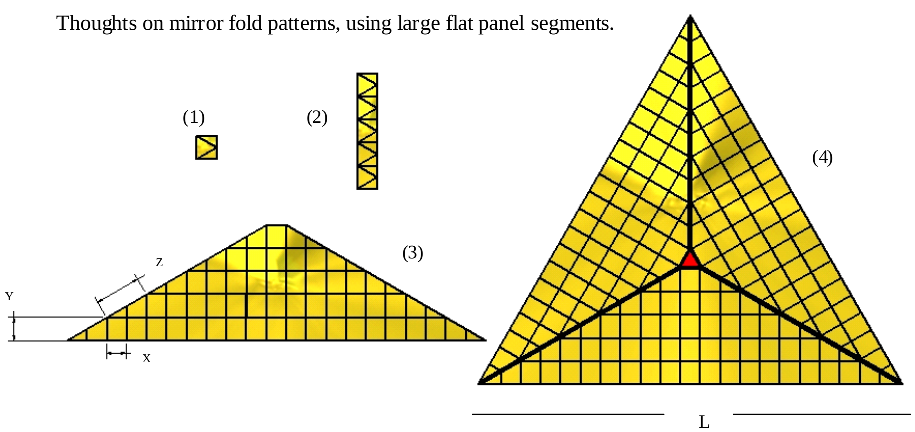


Fig. 13: Deployment sequence.



N = # of rows (odd number) $Y = 2X\tan(30) = 1.16X$ $Z = 2X/\cos(30) = 2.3X$ $L = (4N+1)X$ $A = 0.435L^2$

Example (1): A= 1200 sq m   L=53 m   suppose X=1 m, then N = 52/4. Then N= 13
Example (2): L = 303 m   A= approx 40,000 sq m. Suppose X = 3 m, then (4N+1)3 = 303. Then N=25

Figure 14: Mirror segment pattern unfolds from (1) to (2) to (3).

This is a self-deploying mirror satellite design. Figs 12 & 13 show the beams telescoped in and rotated 90 degrees to fit beside the satellite body. The thin mirror membranes are folded in against the satellite body and between the beams. A fold and unfold pattern for one of the 3 mirror elements is shown in Fig 14.

For deployment once in orbit as shown in Fig. 13, the beams rotate and telescope out and the mirror membrane unfolds and then gets stretched flat by the springs at the ends of the beams.

A significant issue for a mirror based on large-area solar-sail design using thin mirror membranes will be to design for adequate surface flatness in order to obtain the required reflected beam quality.

Being able to orient the mirror satellite so that the reflected sunlight can be directed at a given terrestrial solar farm and held in position as the satellite passes overhead is also a key requirement. Fortunately, the control moment gyros used on the International Space Station (ISS) have the required torque. In [4], a preliminary estimate for the mass characteristics and distribution for the mirror satellite of Fig 11 was given. From this, the moment of inertia, I, for this satellite can be estimated to be $4.7x10^6$ kg m^2. Given the torque, T, for the CMGs on the ISS of 258 Nm, a reasonable slew rate of 5 seconds per degree is calculated suggesting feasibility given a more detailed system design.

VI. ECONOMICS

From the point of view of the DOE Sun Shot program, the key question is the cost to benefit analysis. The DOE states that the current road map price for solar electricity in 2020 is $1.20 per W [9] and that the Sun Shot goal is 6.1 cents per kWh. However, an NREL bottom up analysis states that the achievable price with evolutionary developments will be $1.71 per W [9]. This translates to 8 cents perkWh, short of the goal.

However, the DOE goal is achievable given imagination and the revolutionary space mirror concept described here. Assuming +/- 60 degree 1-axis EW tracking ground stations, then figure 5 shows 8 kWh/m^2 per day of natural sunlight and 6 kWh/m^2 per day of mirror-deflected sunlight. Now assuming good sunny sites and assuming occasional clouds, the numbers might change to 7 and 5. Mirrors then provide 12/7=1.71 times more energy. The next question is cost. The 220 GW of ground sites will cost 220 x $1.71 B = $376 B and assuming the 1st 18 satellites cost $32 B given $1100 per kg but that the next 36 will cost 2x$11B because launch costs will be reduced. Then the cost penalty with added mirrors will be (376+54)/376 = 1.15. Now accounting for more energy but at additional cost, the net advantage is 1.5. Energy costs are then reduced to 8/1.5 = 5.3 cents per kWh. This is exciting! Also, don't forget that solar energy is now available in the evening which might be even more exciting.

VII. MIRROR CONSTELLATION DEVELOPMENT ROADMAP

In [3 & 4], an 18 MiraSolar array constellation in a dawn dusk orbit was compared with the ISC SPS [2] from both a project cost and energy production perspective. The result is shown in Table II. As can be seen, assuming the same mass launch cost of $400/kg from the NASA study [2], the deployment costs are similar but the MiraSolar can produce 18.3 GW vs 1.5 GW on a 24 hour equivalent basis thanks to the assumed existence of the PV ground stations. This represents an 18.3/1.2 = 15 times cost reduction and a cost for the mirrors of only $0.6B/GW, a potentially very economical proposition.

Table II: 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 (W*)	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

While this represents a major step forward, there still remain many challenges. There is still the challenge of a reduced launch cost relative to today's costs and there is the enormity of this project. Fortunately, these two problems are related through the cost reduction associated with economies of scale as suggested by Mankins [10] in Fig 15.

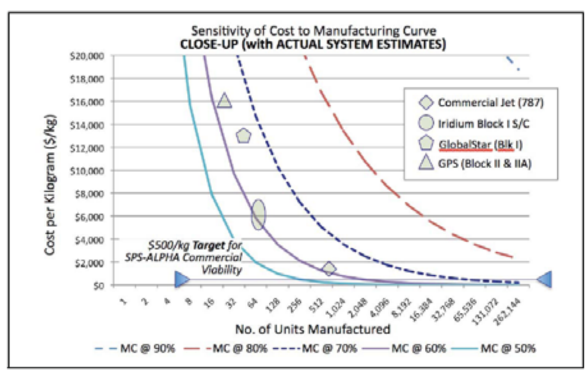


Fig. 15: Placement of selected aerospace examples in the context of Generic Learning Curves [10]

Initially, this project will start with the development of just one mirror satellite of the type shown in Fig. 11. Then as is pointed out in [4], a constellation of just 18 mirror satellites providing illumination at a level comparable to the full moon could be economical for replacing street lights in the evening in city downtown areas. These projects can be handled with today's launch vehicles. But then, this project will progress to the solar electric power constellation as shown in the roadmap in Table III.

TABLE III: DEVELOPMENT ROAD MAP

Steps	Cost Estimate
1. 1st Mirror Satellite for Moonlight for 4 Disney Parks	$20 Million (with R&D)
2. 18 Mirror Satellites for Municipal Street Lighting	$70 Million
3. 18 Mirror Array Constellation for Ground Solar Farms	$32 Billion
4. 2x18 More Mirror Array Constellations for Solar Farms	$2x11 Billion

For the economic analysis of the project for solar electric production, the key question is: how many mirrors satellites are required and what are the launch vehicle and potential launch schedule? The 18 MiraSolar arrays would have 40x40 =1600 mirror satellites (300 m on edge, with area equivalent to 250 m diameter). This means 28,800 for the first 18 array constellation. Fortunately, large capacity launch systems are now being proposed. For example, in the NASA Space Launch System (SLS) now being worked on, each Super Heavy Lift Vehicle can carry 70 MT into orbit [11]. If each Mirror Sat weighs 1.2 MT, the first 18 MiraSolar constellation will require 28,800x1.2/70 = 494 launches given a launch vehicle carrying 70 MT. The first SLS test launch is scheduled in 2017. Hopefully there will be a Super Heavy Lift Cargo Vehicle in full system operation by 2021.

Assuming the learning curves characteristic of Fig 15, it is plausible to assume that a launch cost of about $1000/kg will occur at about 500 launches. With the 3 x 18 full orbit MiraSolar constellation giving 3 hours morning and 3 hours of evening power, the required launches would be about 1500 and launch cost could drop to $500 per kg. 1500 launches at a rate of one per day would require 1500/365 = about 4 years, which would mean that a MiraSolar constellation could potentially be fully operational by 2025.

While the size of this project will be enormous, it is interesting to compare it with another enormous renewable energy project, the Three Gorges Dam project, now operational in China. Table IV compares these two projects. Note that the MiraSolar project capital cost for electric power is lower than for the Three Gorges dam project, the land use ratio is better, and finally, from table III, the start-up costs are lower.

Table IV: MiraSolar comparison with 3 Gorges Dam

Comparison:	Three Gorges Dam	18 Mirror Array Constellation	54 Mirror Array Constellation
Cost	$37 B	$32 B	$54 B
Power (24 hour/day)	22 GW	18 GW*	54 GW*
Electric Power Cost Per 24 hour W*	$1.68 / W	$1.77 / W*	$1 / W*
Land Use	22 GW on 700 km^2	(5 GW on 100 km^2) x 40	(5 GW on 100 km^2) x 40

* Don't confuse the W here with solar peak Watts (W_p). This is corrected to 24 hour equivalent.

VIII. CONCLUSIONS

In order to appreciate the simplicity of the concept described here, one needs to compare it with the earlier Integrated Symmetric Concentrator Space Power Satellite (ICS SPS) shown in Fig 1 and described by Feingold and Carrington [2]. That concept has 2 x 42 large mirror arrays focusing sunlight onto a center satellite body where there are solar cell arrays that receive the sunlight and convert it into electricity and then into a microwave beam. Then the SPS sends energy to a special earth ground station to be converted into electricity. This ICS SPS concept is 5 x 15 km in size and the ground station is 8 km in diameter and this satellite is in GEO 36,000 km above the earth.

By comparison, the concept described here also consists of a large mirror array but the array is in LEO at 1000-km altitude, and the multiple energy conversion steps in space are eliminated and the ground stations are conventional solar cell fields already being built.

Furthermore, while the array proposed for the conventional SPS concept requires assembly in space, mirror elements that are self-deploying and can be launched by today's launch vehicles have been described here.

The NASA Mars rover curiosity project was a spectacular success. However, it cost $2.5 billion. This paper has outlined a more down-to-earth NASA development project that would also be revolutionary and could contribute to solving the world's future energy needs.

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APPENDIX A:

CALCULATIONS RELATED TO TABLE I AND GLOBAL WARMING.

Assume forty 10 km diameter ground sites being illuminated 6 hours per day. This ground area is 40 x 78 sq km = 3120 sq km. Assume that the mirrors are pointed away from the earth unless being directed at these ground sites. So the energy collected by the mirrors beamed down to earth is 1.37 kW x 3.12 x 10^9 x 6 hr/day.

The above can be compared with the solar energy arriving on the earth in a day which is 1.37 kW $(6.4 \times 10^6)^2$ x 3.14 sq m x 24 hr/day = 1.37 kW x 128×10^{12} x 24 hr/day.

The ratio of these two energies is $3.12\times6\times10^9/128\times24\times10^{12} = 0.006\times10^{-3}$ or 6 ppm. Relative to the earth's T of 300 K, this would be a T rise of 1.8×10^{-3}= 0.0018 °C.

Next, let's explore the alternative of generating 220 GW of energy for 14 hours per day with natural gas for a period of 20 years. From the table A1, NG will generate 1.2×10^5 x 453 g / 10^6 BTU. Assume 50% efficiency from heat to electricity and 1 BTU = 3×10^{-4} kWh, then $2\times1.2\times453\times10^5$ g / 300 kWh = 109 g / 300 kWh = 1.1 g / 3 kWh = 0.35 g/kWh

How much CO_2 will be generated by a 220 GW 14 h per day plant in 20 years? 220x14x365x20 GWh = 2.25×10^7 GWh = 2.25×10^{13} kWh. CO_2 displaced is then 2.25x0.35 $\times10^{13}$ g = 8×10^{12} g = 8 teragrams.

From tables A2 and A3, one can see that 10,000 teragrams of CO_2 has led to about 0.4 degrees C of global warming. So, the displaced CO_2 from burning natural gas would reduce global warming by 8x0.4 /1000 C = 0.0032 C. If instead, coal is burned, the CO_2 rise would be 0.0057 C.

Both effects are very small but there is a net benefit for space mirrors of a factor of 3.2 compared to coal burning. Finally, note that the space mirror effect is a single event whereas the CO_2 effect is permanent and cumulative.

Table A1

Fossil Fuel Emission Levels
- Pounds per Billion Btu of Energy Input

Pollutant	**Natural Gas**	**Oil**	**Coal**
Carbon Dioxide	117,000	164,000	208,000
Carbon Monoxide	40	33	208
Nitrogen Oxides	92	448	457
Sulfur Dioxide	1	1,122	2,591
Particulates	7	84	2,744
Mercury	0.000	0.007	0.016

Source: EIA - Natural Gas Issues and Trends 1998

Trends in Global Emissions

Table A2: Global Carbon Dioxide (CO_2) emissions from fossil-fuels 1900-2008

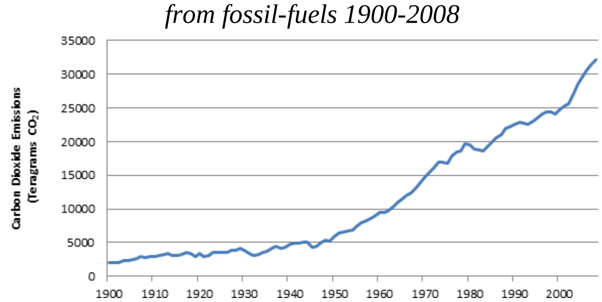

Table A3: Temperature rise in °C.