CASSIOPeiA Solar Power Satellite

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***Abstract*—This paper describes a new Solar Power Satellite (SPS) concept, based on the principle of wavelength-scale modular integration of all major functions, from solar collection through to beam-formation. Like the earlier HESPeruS [1] (Highly Elliptical Solar Power Satellite) concept, CASSIOPeiA (Constant Aperture, Solid-State, Integrated, Orbital Phased Array) has no rotating (or otherwise moving) parts, yet maintains a constant solar collecting area directly facing the Sun (no cosine losses), whilst its retrodirective microwave beam is steered to the terrestrial rectenna (rectifying antenna).**

The well-known beam steering limitations of planar phased arrays require other SPS concepts to have either physically rotating parts, redundant solar collector / RF transmitter area, or suffer cosine losses as the collector tilts away from the Sun. HESPeruS avoids this issue by operating from a highly-elliptical Molniya orbit. By contrast, the novel (patent pending) phased array of CASSIOPeiA permits beam steering through a full 360 degrees without degradation – allowing deployment along a multitude of orbits, including geosynchronous (GSO).

The same ultralight physical substrate is re-used for efficient concentrated photovoltaics, power management / distribution, thermal dissipation and beam formation, with zero temporal redundancy of RF (Radio Frequency) elements. The structure exhibits sufficient self-rigidity to support itself in microgravity without additional trusses, yet is able to deploy from a highly compact stowed configuration – offering the enticing possibility of a fully functional SPS deployed as a single payload.

The paper concludes with a roadmap for staged implementation, offering delivered power from 200 kW (near-space, daylight hours), through 90 MW (3 hour orbit, 23+ hours), to 430 MW of utility-scale baseload power (GSO, 24 hours).

Keywords—SPS; SSP; SBSP; Wireless Power Transfer; WPT

I. INTRODUCTION

In order to meet the objectives of the Paris Climate Agreement, limiting global temperature rise below 2 degrees, the world needs a carbon-neutral sustainable replacement for fossil fuels. With the tide of public opinion turned against nuclear fission, and with fusion still a distant prospect, solar photovoltaics (PV) are emerging as one of the key sustainable energy sources.

However, with a global population expected to peak around 10 billion, massive deployment of terrestrial PV will start to compete with agricultural land usage. Setting aside the issues of utility scale storage and distribution, published data from the largest PV farms in the best US desert locations shows annual power delivery is below 10 W/m^2 (see TABLE I.).

TABLE I. US DESERT PV SOLAR FARM GENERATION

PV Solar Farm	**Completed Installations, 2015-2016 Data**[a]		
	Site Area, km^2	***Generation, GWh p.a.***	***Annual Mean Power Density, MW/km^2***
Topaz	24.6	1283.6	5.95
Desert Sunlight	16.0	1316.6	9.39
Agua Caliente	9.7	1483.2	8.71
Antelope Valley	8.5	616.9	8.28
California Valley	8.0	684.1	9.80

[a] Source: Various

Even allowing for the improved efficiency of multijunction concentrated PV (CPV), this delivered power density is unlikely to improve much; CPV requires 2-axis solar tracking and hence much greater unit spacing to avoid self-shadowing. Taking into account ground-truth (i.e. actual terrain) economic and ecological concerns, the most optimistic deployment of terrestrial PV across all the world's sun-rich deserts is unlikely to meet one-third of the expected 28 TW annual mean power requirement by 2050 (see Fig. 1). Maximum deployment of other terrestrial renewable resources cannot meet this shortfall.

The technical feasibility of SSP (or SBSP, Space-*Based* Solar Power) is proven daily since the first communications satellite (commsat) began operations from geosynchronous orbit (GSO); the only significant difference between commsats and SPS (Solar Power Satellites) is the scale required to capture the majority beam power. Delivered power density of SSP is typically 6.5 times higher than desert solar. SSP requires no utility-scale storage (it is baseload power), is dispatchable to the point of need, and (with elevated mesh-like rectenna construction) could be integrated with other land usage by allowing sunlight and precipitation to pass through.

II. CASSIOPEIA OVERVIEW

CASSIOPeiA (Constant Aperture, Solid State, Integrated, Orbital Phased Array) is a new concept SPS; able to simultaneously maintain (throughout its orbit) ideal Sun-pointing solar collector and Earth-pointing microwave beam, without relative movement/rotation of its parts or temporal redundancy (e.g. multiple antennae used sequentially). This offers significant savings in mass and complexity.

The most salient feature of CASSIOPeiA is its helical structure, loosely resembling a short section of biological DNA, where the double helix twists through 180 degrees.

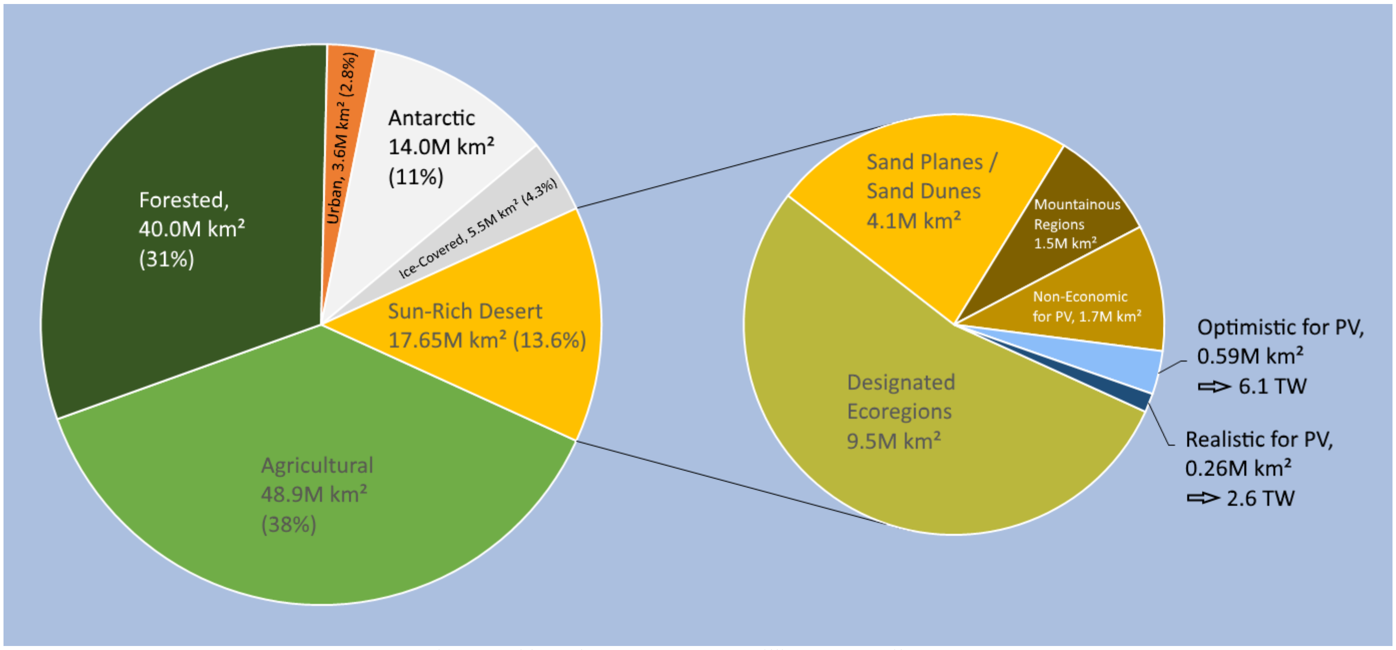

Fig. 1 World Land Area 2012: 129.7 Million Square Kilometres

Analogous to the “base-pair rungs” is the electro-mechanical substrate (see Fig. 2) on which the components and circuitry are mounted. This geometry has equal projected area when viewed from any angle about the twist axis.

A. *Microwave Phased Array*

Excluding the central "housekeeping" section of the satellite, the entire helical structure forms a microwave phased array transmitter, with RF transmitting elements dispersed evenly throughout. Similarly, there are a set of distributed pilot beam receivers, with multiple synchronised sampling of the spherical wavefront phase instances.

Fig. 2 CASSIOPeiA Substrate Model

Each RF element comprises a set of antennae, arranged and controlled such that it emits a cardioid radiation pattern (see IV) in a plane normal to the twist axis, with the null direction steerable through 360 degrees. For a given wavelength, λ, the elements are spaced no more than $\lambda/2$ apart, in order to prevent grating lobes.

It is this combination of steerable null, constant aperture and geometry-independent wavefront phase reversal, which supports the formation and steering of a coherent microwave beam, focused and locked to the target rectenna site.

B. *Concentrated Photovoltaics*

The solar collector has the same projected area as the RF aperture, though optimised for one preferred direction. One orientation of the SPS has the twist axis aligned normal to the ecliptic, such that the satellite rotates once per year to always face the Sun.

Above the atmosphere, there is no scattering of solar radiation – allowing the significant efficiency advantages of CPV to be realised (the record lab efficiency of quad-junction CPV currently stands at 46.0%, compared with 25.3% for 1-sun crystalline silicon – source: NREL). The second advantage of CPV is the reduced area of expensive semiconductor required – inversely related to the concentration factor.

Fig. 3 depicts how a polymer Fresnel lens, planar dielectric reflector, glass Köhler concentrator (see [2]) and CPV chip could integrate with a triple-dipole RF element, without shadowing at visible light or microwave frequencies. The Köhler concentrator ensures even distribution of light across the CPV chip without hot spots. It also provides radiation shielding for the semiconductor in the harsh environment of space.

Unlike the RF elements, the CPV is not evenly distributed across the helical structure; if the central region is at 90° (broadside) to the Sun, then the CPV coverage reduces according to the cosine of this angle, dropping to zero at the solar north/south limits of the array. From this Sun-facing direction, the Fresnel lenses effectively tile the projected area without overlap, with only small losses due to the thickness of the substrate.

C. *Thermal Management*

With the orientation described in II.B, the substrate is edge-on to the Sun. Solar wavelengths outside the dielectric reflectance range pass straight through the planar reflector – and hence do not contribute to heating. A simple thermal conductive layer beneath the CPV, no larger than the Fresnel lens, provides sufficient spreading and re-radiation of waste heat to obviate the need for additional fluid-filled radiators (typical of large-scale concentrator schemes) – offering significant mass savings and reliability improvement.

D. *Electromechanical Aspects*

Electrical interconnect is provided by a multilayer flex-rigid printed circuit, comprising copper, polyimide and PTFE (polytetrafluoroethylene) layers. An overall thickness of 0.4mm is feasible, with additional low profile components, e.g. CPV and ASIC (Application-Specific Integrated Circuit) mounted both sides. The triple antennae of each RF element are formed from the same printed circuit, arranged such that the dipoles are parallel to the twist axis once deployed.

Fig. 2 shows the substrate layers as multiple segments, alternately deviating 15° from the nominal linear extent. This provides a level of rigidity, in the same manner as corrugations in a sheet of paper. The joins between segments in each layer are hinged, allowing zigzag folding of the structure in the plane of each substrate layer, with adjacent segments stowed parallel to each other.

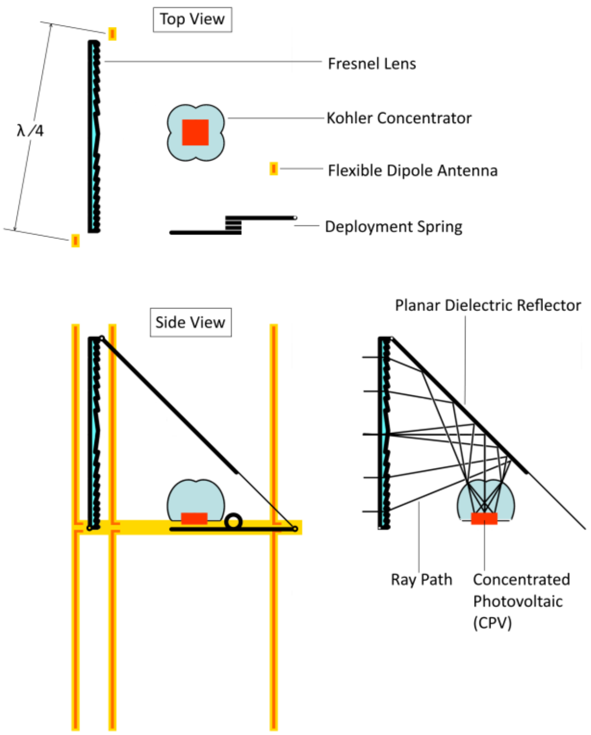

Fig. 3 Integration of CPV with RF Elements

Adjacent layers are joined mechanically by a system of RF-transparent struts and pivot joints, allowing layers to lie flat and parallel with each other. Flexible antennae and folding optics facilitate this. A physical model has been constructed demonstrating how the action of unfolding in the substrate plane causes the layers to separate and subtly twist about a common axis, transforming a stowed compact rectangular stack into a fully deployed, low-density helical structure twisted through 180°.

III. SYSTEM DESIGN PARAMETERS

The design follows from the choice of power beam frequency and operational altitude. Beyond 10 GHz, atmospheric beam losses increase substantially. However, for a given altitude and transmitter aperture, the minimum terrestrial beam spot diameter grows proportionally with wavelength – so diluting the delivered power density if the frequency is too low.

The optimum available frequency is 5.8 GHz, an internationally recognised, unlicenced ISM (Industrial, Scientific and Medical) band, having a wavelength, λ, of 51.7 mm (2.04 inches). At this frequency, atmospheric losses are <0.3 dB down to 15° elevation for CD 0.99, i.e. transmission is better that 93.3% for a Cumulative Distribution of "99% weather", which includes heavy cloud and storms. For a zenith beam, this loss is less than 0.05 dB (98.8% transmission, CD = 0.99) [3].

From GSO altitude (35,786 km), the minimum beam spot diameter (i.e. the Airy disc containing 84% of the beam power, typically captured by the rectenna) is given by (1):

$$D_{RX} = 2.44 \times \lambda \times R / D_{TX} \tag{1}$$

Where D_{RX} and D_{TX} are the receiver (rectenna) and transmitter diameters, and R is the beaming distance (35,786 km). For a transmitter diameter/length of 1.43 km at GSO, the minimum rectenna diameter to capture the Airy disc is 3.16 km. The aperture is the sinusoidal projected area (2):

$$A_{TX} = 2 \times D_{TX}^2 / \pi = 1.3\text{E}6 \text{ m}^2 \tag{2}$$

Which, at AM0 (Air Mass Zero solar intensity = 1,365 W/m^2 at one astronomical unit, 1AU) intercepts 1.77 GW of sunlight. Assuming 40% efficient CPV and 85% DC:RF conversion efficiency, this gives a total RF power, P_0, of 600 MW. The peak beam intensity is given by (3):

$$I_0 = P_0 \times A_{TX} / (\lambda^2 \times R^2) = 228 \text{ W/m}^2 \tag{3}$$

A consensus environmentally safe microwave peak beam intensity of 230 W/m^2 (approximately one-quarter the intensity of noon sunlight) has been used in several previous SSP studies, including [4]. This is the second key parameter, after λ, which guides the optimum SPS diameter for a given beaming distance.

Using the figures above, and a typical RF:DC efficiency of 85%, the delivered power is 430 MW_{DC}; an average of 55 W/m^2 for the 3.16 km rectenna.

IV. PHASED ARRAY SIMULATION AND RESULTS

The steerable cardioid radiation pattern was modelled for three half-wave dipoles spaced λ/4 apart, forming one RF element (see Fig. 4).

Next, these elements were arranged on a virtual helical surface; 7 elements per-row, spaced λ/2, 11 rows, with 180°/11 twist between each row, vertically offset such that the end elements on adjacent rows were also spaced λ/2.

For comparison, an equivalent planar array was also modelled: 7 vertical half-wave dipole elements (spaced λ/2 horizontally) per row, and 11 parallel rows spaced vertically as for the helical array. This planar array had no rear reflector, hence radiated equally (mirrored) about the plane. Total power was made equal, and split evenly between all elements.

Fig. 5 compares these arrays on a log-angle plot from 0° (planar end-fire) to 90° (planar bore-sight). Note how, for the planar array, the main lobe from 0° to 45° is asymmetric, with a significant component along the plane, whereas CASSIOPeiA maintains symmetry for both main and side-lobes throughout. The planar main lobe has narrower 3dB width at boresight; due to its π/2 greater aperture at this angle.

A larger 16×25 helical array was also modelled. Polar plots are shown for both azimuth and elevation (Fig. 6). It can be seen that the pattern of peak beam intensities is very similar to the omnidirectional radiation pattern of a single half-wave dipole; for instance, the 3dB elevation dipole radiation pattern and CASSIOPeiA steering limit are both ±55°. The azimuth plot shows various beaming angles covering the 360° range, for both 0° and 55° elevations – the slight deviation from the dipole azimuth pattern is possibly an artifact of the small model size and short focal distance.

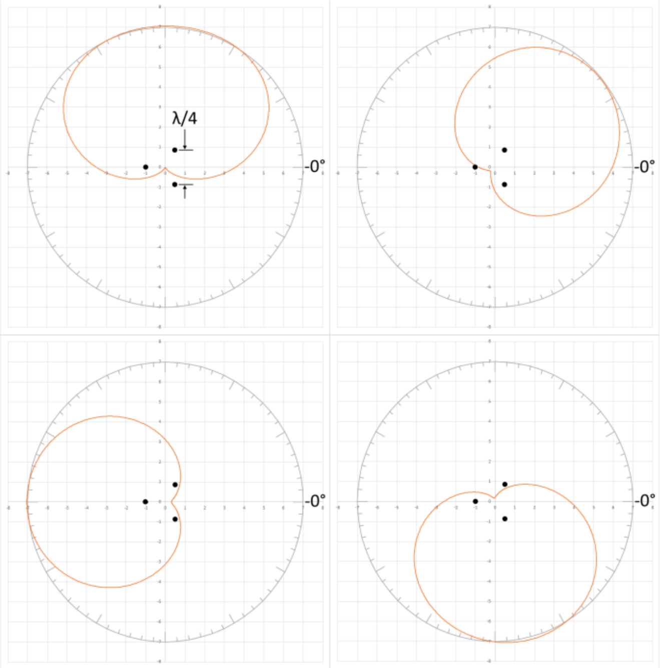

Fig. 4 Cardioid Pattern Steered Through 360°

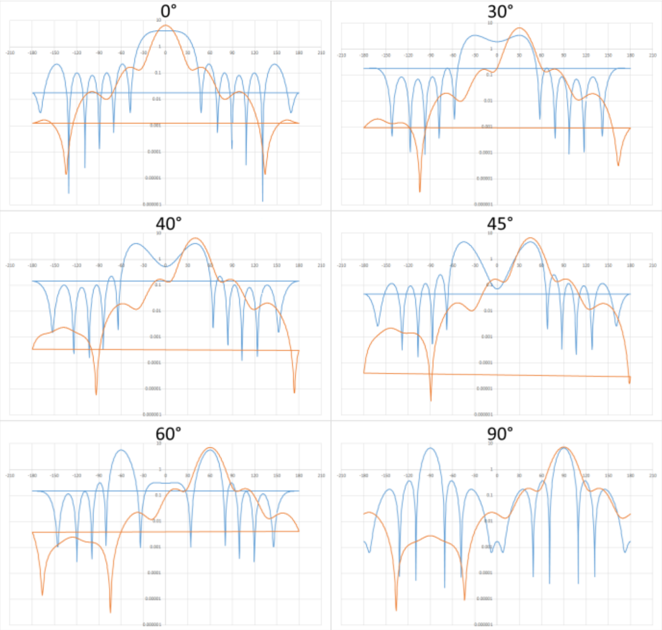

Fig. 5 CASSIOPeiA vs Equivalent Planar Phased Array

Fig. 7 shows the beam profile focused at a close-range

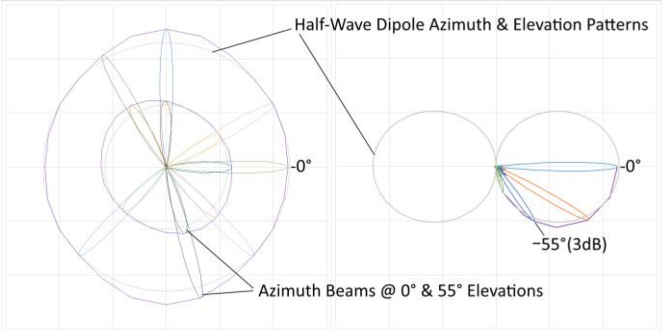

Fig. 6 CASSIOPeiA Beam Steering vs Dipole Pattern

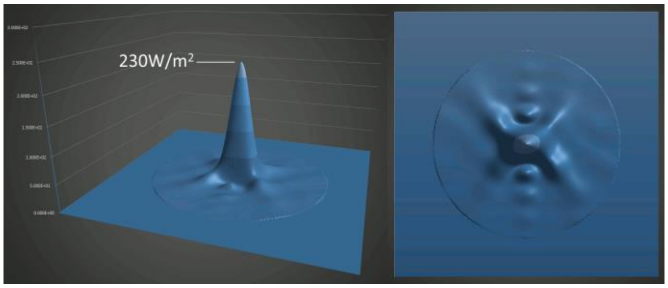

Fig. 7 CASSIOPeiA Airy Disc & Beam Profile

target, showing only small deviations from an ideal Airy pattern for diffraction-limited optics.

V. ROADMAP TO GEOSYNCHRONOUS ORBIT

The perceived wisdom has been that SSP does not scale economically below gigawatt power delivery. This reasoning is based on high launch costs (USD 10,000/kg to LEO) and a transmit antenna that has to be at kilometre scale (due to diffraction optics from GSO) irrespective of beam power. Given the investment in the high-mass microwave antenna, economic considerations dictate that the comparatively low-mass solar collector is larger, to maximise the power available. This either leads to kilometre scale solar concentration (e.g. sandwich module [5] concepts), and the necessity for additional waste heat radiators, or an electrical power bottleneck and substantial engineering challenge at the rotating joint(s).

By eliminating the rotating joint (either optical or electrical), without suffering cosine losses or beam-steer limitations, this paradigm can be broken.

A. *Near-Space Applications*

The first step is to garner public acceptance of power beaming by providing useful, safe, power delivery to high-value customers.

Significant progress has been made recently in stratospheric platforms, including Thales Alenia Space Consortium's "StratoBus", providing many of the capabilities of a satellite, plus the benefit of serviceability, without the space launch costs. The stratosphere is a region above all weather, providing high DNI (direct normal irradiance) sunlight throughout daylight hours.

CASSIOPeiA is a good candidate for deployment in the stratosphere; its low mass, compact stowed form and unprecedented solid-state beam steering capability is ideal for placement within a stratospheric blimp (Fig. 8). Solar tracking from dawn to dusk is provided by controlling roll and yaw of the entire platform using its station-keeping capability. From 20 km altitude, the beam can remain locked on a rectenna sited within a 28 km ground radius.

Using equations (1), (2) and (3), plus reduced expectations of CPV efficiency (reduced concentration for greater solar acceptance angle), a 34 metre diameter CASSIOPeiA massing 200 kg – 400 kg could deliver 100 - 200 kW_{DC} to a 74 metre diameter temporary (relocatable) rectenna, with a peak beam intensity below the 230 W/m^2 safe limit.

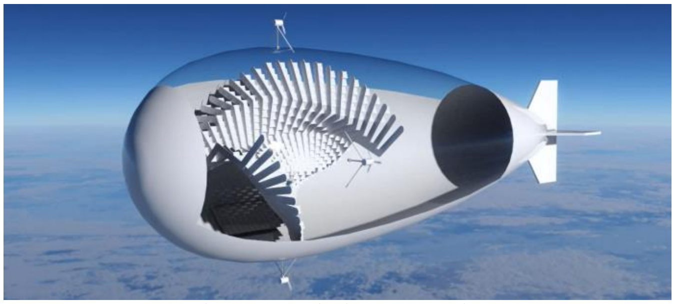

Fig. 8 Stratospheric CASSIOPeiA

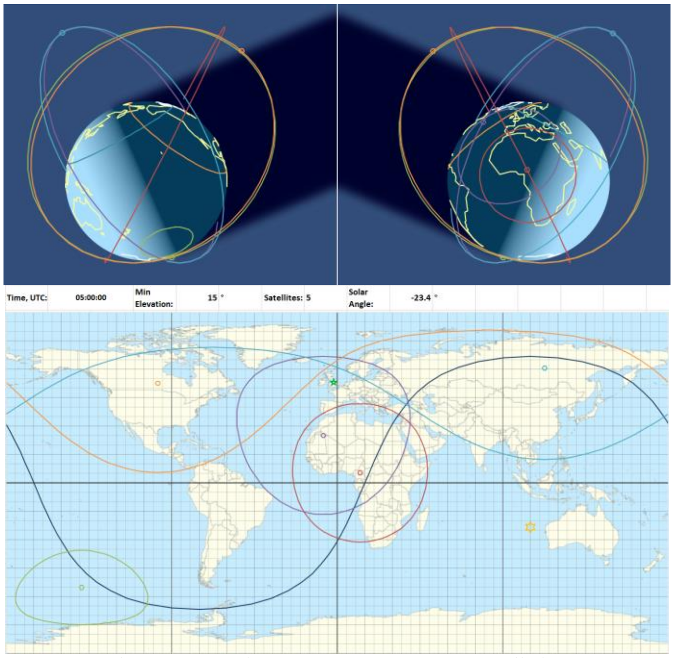

Fig. 9 Sun-Synchronous, 3 Hour, 5-SPS Constellation

B. *Low Earth Orbits (LEO)*

One reason to move solar power into space is to avoid the diurnal cycle. At 380 km altitude (typical), the ISS (International Space Station) experiences a sunrise or sunset every 46 minutes so clearly could not serve as an existing platform for baseload power.

Sun-synchronous (SS) orbits use Earth's oblateness to rotate the orbital plane by approximately 1° per day, maintaining the same orientation to the Sun throughout the year. Perhaps the best-known is the 98° inclination "dusk-to-dawn", where the satellite follows the terminator; never entering Earth's shadow. However, the 98 minute period and scarcity of polar region power customers makes this less favourable for SSP.

One 3-hour SS orbit has been modelled in detail (Fig. 9). With 116.6° inclination, 963 km perigee and 7,414 km apogee altitude, this elliptical orbit has extended loiter in the northern hemisphere, skipping over Earth's shadow even during mid-winter. When joined by four additional SPS's with orbital planes offset by 72°, this 5 satellite constellation can deliver continuous power to a northern latitude rectenna site exceeding 23 hours/day, with concurrent (though intermittant) delivery to other sites around the globe.

Each CASSIOPeiA satellite (Fig. 10, showing 90° and sun-facing directions) would measure 650 metres across (minimum rectenna diameter: 1.45 km) and mass between 90 and 180 tonnes – overlapping the capability of near future planned heavy-lift launch vehicles. With no need for on-orbit construction, this greatly reduces the challenges to achieving commercial SSP. Delivered power is 90 MW, or >750 GWh per annum (at 23 hours/day), similar in output to some current

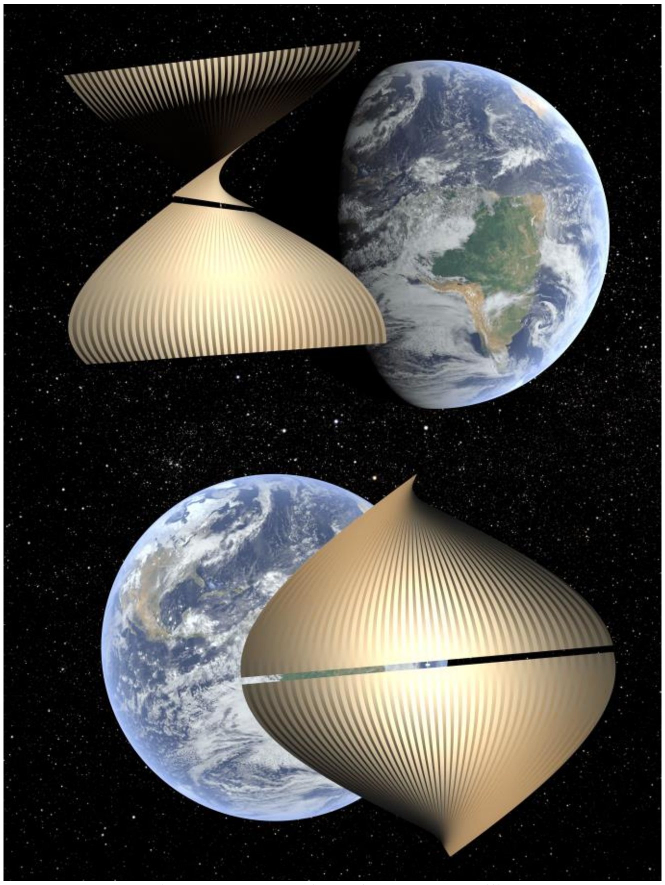

Fig. 10 CASSIOPeiA Solar Power Satellite

desert PV farms, but consistently available to far northern climes without significant (if any) storage required.

C. *Geosynchronous Orbits*

For SSP, the kilometre-scale transmitter requirements imposed by microwave diffraction optics below 10 GHz, requiring multiple launches and on-orbit construction, would appear to favour Sun-synchronous LEO options over GSO.

However, the beaming footprints shown in Fig. 9 are limited principally by the minimum elevation at the rectenna. At 15°, the rectenna must grow by a factor of 3.86 (1/sine) along the direction towards the SPS.

As each rectenna site is served by at least 5 satellites in different orbital planes, in practice this means the rectenna area needs to grow by the square of this factor (×14.9), reducing the mean delivered power density to 3.7 W/m^2 (assuming the 230 W/m^2 safe beam limit holds). This is below that of the best desert solar farms – though still highly significant, given its predictability in low-insolation northern regions.

If we commit to replacing fossil fuels by mid-century, amongst the mix of other sustainable solutions, we will need perhaps 20 TW of reliable high-density power (to meet the 28 TW predicted requirement) – which is something that GSO power-beaming satellites could provide with little adverse impact on the environment.

With CASSIOPeiA deployed at GSO in a near-equatorial plane, each 1.43 km satellite would mass between 400 and 900 tonnes, delivering 430 MW to a rectenna measuring 3.16 km diameter (measured in the east-west direction; greater measured north-south, according to latitude).

VI. CONCLUSION

Only since the Industrial Revolution (1760 – 1830) have levels of atmospheric CO2 exceeded those of the previous 800,000 years [6], far longer than modern humans have existed. The role of CO2 in human-induced climate change is unequivocal, a situation not helped by the on-going reduction of carbon-absorbing forest cover in favour of agriculture (Fig. 1). The expected 3 billion population rise will require increases in both food and the sustainable energy necessary for prosperity.

The exponential increase seen in terrestrial solar power, coupled with a similar decrease in USD-per-watt has seen some recent displacement of coal. However, these market pressures are likely insufficient to drive large-scale replacement of fossil fuels, given the foreseen conflicts over land usage.

Space Solar Power, alongside other sustainable energy resources, has the potential to meet all of humanity's needs – without adversely affecting the environment or impacting food production. The major hurdles have been the huge financial and technical risks involved in constructing the first utility-scale SPS – both potentially greater than the 150 billion USD spent during ISS construction.

CASSIOPeiA offers a means to initiate beamed solar power from near-space in the next few years, establishing a market for the reusable launch vehicles to follow. The simplicities and mass-savings inherent in a solid state design will enable a single payload, self-deploying SPS to pay back the energy costs over the first few months of operation, retiring the technical and financial risks before progress is made towards multi-terrawatt levels of power delivery from geosynchronous orbit.

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