Acta Astronautica 159 (2019) 170–178

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

CASSIOPeiA – A new paradigm for space solar power

Ian Cash*

International Electric Company Limited, United Kingdom

ABSTRACT

Recent debate (Clack v. Jacobson, 2017) argues the feasibility of 100% terrestrial renewables (wind, water, solar) by 2050, on the premise of restricting world consumption to 2012 levels (~12 TW-years). Given the expected population rise by 3 billion over the same time frame, and the correlation between prosperity and energy availability – are we to impose energy equality, requiring some to reduce consumption by 87%, or are we to condemn the majority to relentless poverty? Choosing neither implies ever-increasing carbon emissions and the risk of catastrophic climate change. Nuclear fission is one energy technology which could be expanded to provide sufficient carbon-free power, but faces widespread opposition from public fear and distrust. Future terrestrial fusion is another, but first pilot operations are not expected until 2050 – which may be too late. We could make much better use of one existing fusion power source, our Sun. The fundamentals of Space Solar Power (SSP) are well understood and could lead to a world of energy abundance; the deliverable energy from just a 10 km geostationary (GEO) band exceeds 570 TW-years – enough to supply ten billion people at six-times current US per-capita levels. Despite this, SSP has languished for fifty years. GEO is one of few candidates for baseload power, but physics dictates a kilometre-scale microwave transmitter irrespective of the power delivered – hence economics favours the multi-gigawatt (per-satellite) engineering limit. Given the complexity of the differentially rotating solar collector, sub-gigawatt SSP suffers both economically and technically, with different solutions required at different scales – which has led to exorbitant (hence prohibitive) start-up costs. CASSIOPeiA breaks this non-scaling paradigm by eliminating the rotating interfaces; all SPS subsystems are able to share one lightweight modular structure, with near-invariant areal power density from sub-megawatt to gigawatt systems. With additional fixed mirror concentrators, CASSIOPeiA can also be expanded into the multi-gigawatt regime. CASSIOPeiA's unique beam-steering capability facilitates baseload delivery from alternative, closer orbits, with the possibility of single payload deployment requiring no on-orbit assembly. By starting with sub-megawatt, near-term stratospheric station-keeping platforms – with retrieval, servicing and transfer of gained knowledge – the era of SSP may commence at much lower risk and expense.

1. Introduction

CASSIOPeiA – Constant Aperture, Solid-State, Integrated, Orbital Phased Array – is a new format microwave antenna (worldwide patent applied) suitable, amongst other applications, for wireless power transfer in a space environment. In particular, when integrated with high efficiency photovoltaics (PV), CASSIOPeiA may form the basis of a utility-scale Solar Power Satellite (SPS) having unprecedented specific power, helping contribute towards the world's growing need for sources of clean, sustainable and reliable energy.

1.1. Satisfying the growing demand for power

The World Energy Council predicts that Total Primary Energy Supply (TPES) is expected to grow from 18 TW-years (2015) to 28 TW-years (2050) under the Jazz scenario [1]. This is driven by rising population, economic development and a justified aspiration by the underprivileged to improve their standard of living. At the same time, there is similar recognition that the growing use of fossil fuels is both unsustainable and dangerous to the environment.

Electricity currently comprises one-fifth of total consumption, but this most-versatile form of power could grow to dominate the mix; already evidenced by increased electrification of public transport networks, private vehicles and personal mobility, by the growing adoption of electric heat-pumps as the most efficient means of providing both warmth and cooling, and by the early (but significant) developments in electro-chemical (carbon-neutral) fuel-synthesis as a means to supply air transport and shipping - where future expectations of battery technology still fall short of requirements, but also where fuel-cell advances could complete this trend.

A sustainable large-scale increase in electrical supply could be delivered by improvements to nuclear power, such as significantly raising the meagre 1% burn-to-waste ratio [2]. However, the global appetite for nuclear has waned following the accidents at Chernobyl and Fukushima, with many governments vowing to cancel new investments as existing plants shut down. The promise of clean, inexhaustible, fusion power remains beyond the 2050 horizon, with no clear alternative to giant tokomaks (such as ITER [3]) having yet emerged to shorten this development timescale.

Existing predictable and reliable forms of sustainable power include hydroelectric, geothermal, ocean-thermal and tidal power. These require specific geological/topographic attributes available only at

---

* Corresponding author.
E-mail address: ijcash@internationalelectric.com.

https://doi.org/10.1016/j.actaastro.2019.03.063
Received 13 December 2018; Received in revised form 3 February 2019; Accepted 21 March 2019

certain geographic locations - most of which are already identified. Many are fraught with ecological concerns, or suffer extreme technological and economic challenges in transporting power from where it is available (e.g. deep ocean) to where it is required (e.g. population centres).

Solar power and its derivatives, wind and wave power, offers the greatest potential for growth in sustainable supply. However, the unreliability of these terrestrial forms creates severe challenges - the full scale of which are under-appreciated. The enormous potential of delivering solar power from a non-terrestrial source, i.e. space, has almost zero public awareness - yet its technical feasibility and reliability has been proven on a daily basis, ever since the first photovoltaic-powered communications satellites began relaying microwave signals from orbit.

1.2. The need for baseload power

For a regional or national electric power grid, the Base Load is the minimum demand seen during a multi-day period. This demand has been traditionally met by coal, nuclear and gas-fired combined-cycle generation - which are unsuited to (or incapable of) varying their output to match demand changes within a day. The remainder of the demand is met by Dispatchable generation; systems which can vary their output within seconds up to a few hours.

There has been much reporting of the rapid growth in terrestrial renewables (particularly wind and solar) and their falling costs, leading to a somewhat naive expectation that these will soon begin replacing existing fossil-fuelled power plants around the world. This growth should be welcomed, but it should also be recognised that this has not been matched by similar growth in grid-scale storage - needed for the regular, unpredictable and extended periods when output is minimal or zero. At present, this shortfall is mostly met by additional gas-fired capacity in the form of low-efficiency peaking plants, which now not-only have to cope with variability of demand, but also with unpredictable loss of supply.

Excluding location-specific storage schemes such as pumped hydro, most large-scale storage proposals are still in their developmental infancy. Of these, lithium battery storage is salient, driven by the growth of mobile devices and electric/hybrid vehicles. Battery storage has the benefit of near-instant availability, coupled with high round-trip efficiency of around 80%.

Amongst the largest completed grid-scale Li-ion projects is the Tesla Hornsdale Power Reserve [4], at a reported cost of $50 M for 129 MWh. The current most-productive US solar PV farm is the 579-MW nameplate capacity crystalline silicon (c-Si) Solar Star [5] (Rosamond, California), completed in June 2015. It is an informative exercise to consider what it would take to combine these Li-ion and PV installations, in order to match the capabilities of a single gigawatt fossil-fuelled plant.

From 2015/2016 data for the months of December and January, Solar Star delivered a daily mean power of 112 MW (2688 MW-h). During these months, local insolation averages 3 sun-hours per day. So, to approach 1 GW (24 GW-h) of predictable baseload power, assuming 80% round-trip battery storage efficiency, this would require 3 GW-h of direct delivery and 21/0.8 = 26.25 GW-h cycled through storage, a 10.9-times (29,250/2688) PV and 163-times (21,000/129) battery scale-up. Given the purported $500 M cost of Solar Star and $50 M cost of the Hornsdale Power Reserve, this would value the completed installation at $13.6 B. This compares unfavourably to a typical $700 M build cost for a 1 GW gas-fired plant or $5.5 B for nuclear. Such a solar baseload installation would require approximately 13,000 ha (32,000 acres) per gigawatt, compared to just 15ha (37 acres) for gas or 450ha (1100 acres) for nuclear (the latter being a 2 GW example).

It should also be recognised that this solar-baseload combination still provides no guarantee against power shortfall, e.g. should there be more than one consecutive cloudy day. This is especially relevant to wind power; the UK recently experienced a “wind drought” during June/July of 2018. This amounted to a 40% drop in July output compared to the previous year, despite a 10% increase in installed capacity.

1.3. The economic benefits of Space Solar Power (SSP)

Given an academic free-reign exercise to maximise collection of solar photons at 1AU distance onto a fixed photovoltaic area, few would choose to place a solar receiver far from the equator on a rotating sphere, averaging 12 h per day in darkness, under a thick atmospheric blanket subject to a random distribution of absorbing and reflective cloud layers.

By choosing a suitable orbit, such-as a geo-synchronous orbit (GSO), a SPS can be bathed in sunlight 24 h per day[*], whilst simultaneously being in view of one or more terrestrial receiving stations. By choosing a frequency below 10 GHz, solar power can be converted to microwaves and continuously beamed to the ground station with minimal atmospheric loss - irrespective of weather or the diurnal cycle[†].

This has been known for 50 years, with the technical ability to demonstrate the requisite hardware in-situ also available since this time. However, the (atmosphere-limited) transmission frequency is subject to diffraction physics - meaning that to focus a beam down to a spot size matching the transmit antenna from geosynchronous orbit requires a transmitter which is at-least 1.6 km in diameter (@ 10 GHz), independent of the actual transmitted power - meaning that power levels must be maximised to justify the construction costs. No facility of this scale has ever been constructed on-orbit and numerous studies since the 1970's have concluded that Space-Based Solar Power (SBSP) would be prohibitively expensive.

The original 1979 NASA Reference SPS [6] (Fig. 1) considered both 1-sun c-Si and 2-sun gallium arsenide (GaAs) PV variants, massing 51,000 tonnes and 34,000 T respectively, both delivering 5 GW to the terrestrial grid via a two-axis gimballed phased array antenna measuring 1 km across, beaming microwave power at 2.45 GHz. With the output averaged over the 10 × 13 km diameter rectifying antenna (rectenna), this requires 2000 ha per gigawatt. Despite major PV improvements, the physics of microwave diffraction require the dimensions of antenna and rectenna remain the same today.

With today's launch price to geosynchronous transfer orbit (GTO) at $11,300 per kilogram [7] (SpaceX Falcon 9 or Falcon Heavy), assuming equal mass for circularisation propellant, this would entail a per-gigawatt cost of $230 B or $154 B respectively (ignoring materials and construction costs), i.e. a launch price of up to $1.15 trillion.

Two factors have emerged within the last two years:

1.4. Reusable space launch

Partially reusable space launch[‡] has been demonstrated by SpaceX, most dramatically with the recent simultaneous propulsive landing of twin booster stages during the inaugural flight of Falcon Heavy. The same company is now in development of a fully reusable two stage system “Big Falcon Rocket/Spaceship” (BFR/BFS), with the third iteration capable of lofting 100 T to Low Earth Orbit (LEO). Assuming an initial ten BFR reuses and market competitors such as Blue Origin also pursuing reusability, the BFR launch price should hit $100 M (SpaceX claim they can reach $7 M). After including an extra launch for refuelling the second stage (BFS), it is considered capable for placing 75 T onto GTO, which is 40 T at GSO following circularisation, i.e. a launch price of ~$5000 per kilogram.

---

[*] Excepting a few days of < 70-min outages during March/September equinox periods.

[†] Optical or infra-red laser SPS is also feasible, but suffers the same weather dependency as terrestrial solar.

[‡] The STS system (1981–2011) required significant refurbishment – in some cases exceeding new-build cost.

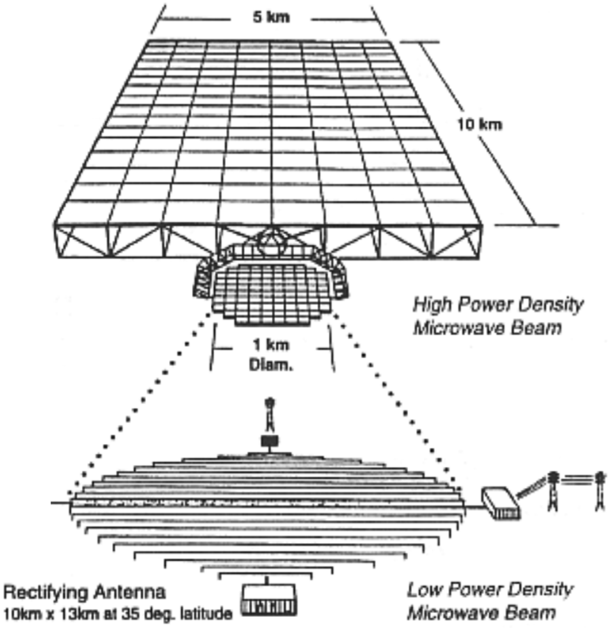

Fig. 1. Nasa 1979 reference system.

1.5. *CASSIOPeiA SPS concept*

The operating principle of CASSIOPeiA has been independently validated by the University of Strathclyde, UK. Constructed from ultra-lightweight materials, detailed and conservative modelling shows a 2 GW_{AC} variant should mass just 2,000 T, i.e. a baseload specific power of 1 kW/kg – approximately 5-times greater than the nearest alternative baseload-capable SPS concept.

Having CASSIOPeiA combined with BFR/BFS successfully meeting their design specifications ($100 M per launch, 100 T to LEO, 1 kW/kg delivered baseload power), the launch cost of utility scale sustainable baseload power falls to $5 B per gigawatt, a 46-times like-for-like improvement over the 1979 c-Si reference model, at 2018 dollars.

Using simplified Levelised Cost of Energy (LCOE) analysis over a 20-year lifetime (3.5% discount, no servicing) gives $48 per MW-h for CASSIOPeiA-based SSP, below that projected for other sources (Table 1).

Should SpaceX meet its aspirational target of 100 reuses, a further 10-times reduction in launch price is feasible.

To understand how an SPS can achieve such continuous specific power, it is necessary to appreciate the fundamental challenges and opportunities of Space Solar, and how they are both mitigated and capitalised by the CASSIOPeiA design.

Table 1
Projected LCOE [8].

Projected LCOE (US, by 2020)	
Generation Source	$/MW-h (avg)
Wind (offshore)	197
Natural Gas (conventional)	142
Solar PV	125
Advanced Nuclear	95
Coal (conventional)	95
Hydro	84
Wind (onshore)	74
Natural Gas (combined cycle)	73
Geothermal	48

2. Comparison OF SPS concepts

There are many ways to categorise the in-space segment of SSP. However, all concepts capable of invariant (throughout the orbit) terrestrial power delivery have one aspect in common: a means to overcome the rotational mismatch between the satellite's Sun-pointing and Earth-pointing sub-systems. These fall into one of the following categories:

i) Electrical power over articulated joint(s):

NASA 1979 Reference System,
CAST Multi Rotary Joint (MRJ) [9]

ii) Optical power over articulated joint(s):

Modular Symmetrical Concentrator
(MSC), SPS-ALPHA [10]

iii) Solid-state with redundant apparatus:

Tin Can SPS (multiple redundant PV)

iv) Solid-state other:

CASSIOPeiA SPS [11]

Concepts in category i) concentrate electrical power through the cross-sectional area of their rotating interface(s) - which is much smaller than the area of the PV array and the transmitter aperture - hence a concentration of power requiring special consideration of losses and thermal dissipation. In addition, the mean power distribution path from PV to RF-PA may be measured in kilometres, requiring the use of high voltages to minimise the current-squared resistive losses. This may add significantly to the mass budget and requires significant attention to insulation in a vacuum environment to prevent arcing. The issue of single-point failure is addressed by the CAST MRJ design, which divides the power distribution across multiple rotating joints.

Concepts in category ii) use lightweight articulated reflectors to pass power optically over the rotational interface, concentrating sunlight onto a Sandwich Panel arrangement comprising photovoltaics, a sub-metre scale power distribution middle layer and an Earth-facing outer layer of RF phased array power transmitting antenna. Sandwich panels may reduce distribution losses by three or greater orders of magnitude, in direct proportion to the reduced distribution path length. The Symmetrical Concentrator has a single failure point associated with the axis of rotation of the primary reflectors, whether this comprises a mechanical joint or a free-flying control system balancing photon pressure against microgravity forces. SPS-ALPHA avoids this by utilising a sophisticated system of multiple, self-powered, 2-axis sun-tracking reflector modules mounted on a framework which is essentially rigid to the sandwich panel.

Category iii) concepts utilise either redundant PV, redundant transmit antennae, or both. The “Tin Can” SPS comprises a cylindrical arrangement of PV with its axis normal to the orbital plane, together with an attached open “lid” – which is the Earth-facing phased array transmit antenna. The advantage is the eliminated complexity of articulated joints, offering the high system reliability and long lifetime of a solid-state design. This concept still has the losses associated with a long power distribution path and requires more than three times the photovoltaic area, compared with a Sun-facing flat PV array.

3. Concept design

The CASSIOPeiA SPS (Fig. 2) is unique for a solid-state design in having no temporally redundant parts; i.e. all PV receives constant maximal insolation and all RF elements contribute to the power beam

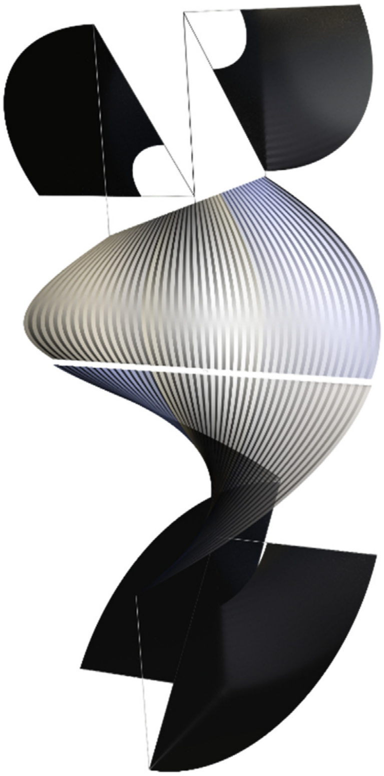

Fig. 2. CASSIOPeiA SPS, 1 GW (GSO) variant having 1-sun quadrant planar reflectors.

throughout its orbit. It achieves this by maintaining a constant attitude with respect to the Sun, whilst steering the power beam through 360° azimuth and up-to ± 39° elevation (3 dB point) to always point at the receiving station.

3.1. Novel phased array

A typical dense planar phased array, optimised for a wavelength λ, has elements spaced no more than ½λ (square lattice) or λ/√3 (triangular lattice) to prevent grating lobes. This results in approximately ± 45° beam steering capability with respect to a boresight direction normal to the plane. All such arrays utilise a reflective ground plane, without which there would be two main lobes mirrored about the plane. Advances in low-profile printed patch antenna designs over recent decades make them highly suitable for such array elements.

Conformal arrays can be considered as comprising multiple planar array segments following a surface curved about one or more axes, such as an aircraft wing or fuselage. Clearly, a cylindrical conformal array is able to smoothly and continuously steer a single beam through 360° - but it does this at a cost; planar segments with boresight tilted further than 45° from the beaming direction offer little power contribution to the main lobe, leaving 75% of the array unused at any instant. The same reasoning applies to a helical arrangement twisted through 360°.

CASSIOPeiA differs from the classic phased array by utilising elements with inherent 360° steering capability. Each element comprises three omnidirectional antennae (such as ½λ dipoles) with centres spaced approximately ¼λ apart. By controlling the relative magnitude and phase of currents for each antenna in the element, a cardioid radiation pattern (Fig. 3) can be established with a null/minima in any chosen “rear” direction, obviating the need for a rear reflector. For the special cases where the null direction aligns exactly with two of the three antennae, the current in the third antenna is zero. This corresponds to the simpler case of two dipoles spaced ¼λ apart, fed with equal magnitude currents and 90° phase difference. It can easily be shown that electromagnetic waves add in the forward direction and cancel in the reverse.

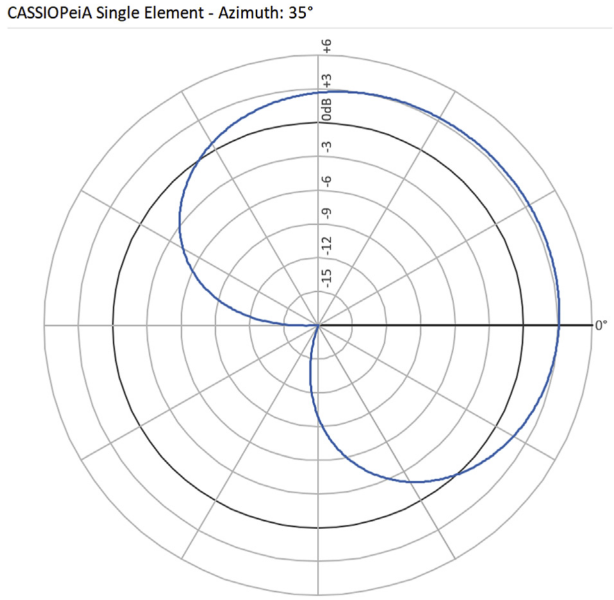

Fig. 3. Cardioid radiation pattern of optimised triple dipole element, steered to 35°.

The general case for the far-field response of multiple centre-fed dipoles can be derived from the Poynting Vector by summing the electric interference pattern due to the dipole currents I_0 at radial distance r ($r \gg \lambda$) and elevation angle θ (the dipole radiation pattern being invariant with azimuth angle φ):

$$E_\theta \approx jZ_0 \frac{e^{-jkr}}{2\pi r} I_0 \left[\frac{\cos\left(\frac{kL}{2}\cos\theta\right) - \cos\left(\frac{kL}{2}\right)}{\sin\theta} \right]$$

$$\left(k = \frac{2\pi}{\lambda}\right) \qquad [1]$$

where Z_0 is the characteristic free-space impedance (~377 Ω) and L is the dipole length – which zeros the last cosine term when equal to half-wavelength. The surface intensity is then easily determined for each unit area as E_0^2/Z_0.

By arranging triple-dipole elements on a virtual helical surface twisted through 180°, having diameter D and height H, it can be shown that the aperture (projected area) viewed from any azimuth angle is a constant, 2 × D × H/π. This virtual helical surface can be divided into multiple narrow physical layers having linear extent D, upon which the elements are mounted (Fig. 4). For ½λ dipole antennae, the attachment point is the central electrical feed, making each layer also the local ground plane for its associated elements. The layer spacing must exceed ¼λ, such that each monopole is clear of adjacent layers, but is restricted such that no element is spaced further than λ/√3 from its four nearest neighbours across the virtual helical surface (to prevent grating lobes).

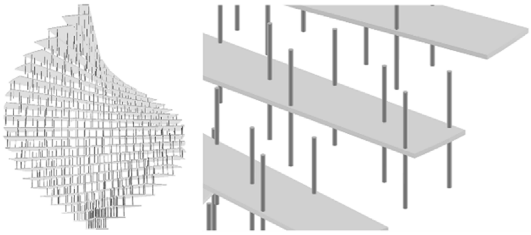

Fig. 4. Small-scale CASSIOPeiA phased array, detailing helically arranged triple-dipole elements.

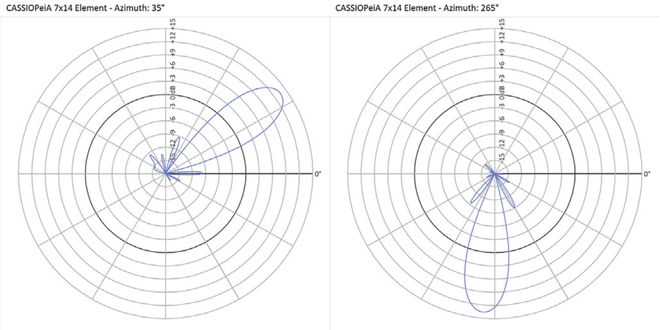

Fig. 5. Small-scale (98-element) CASSIOPeiA array, steered to 35° and 265° azimuth.

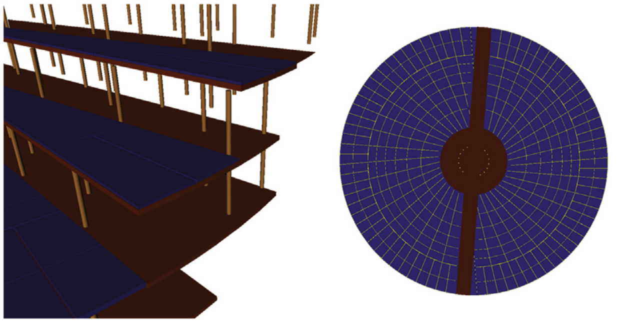

Fig. 6. CASSIOPeiA array integrated with PV, individual layers and orthographic polar view.

In practice, this means a smooth transition between triangular and rectangular lattices for an optimal arrangement of elements.

At small scales (Fig. 5), having relatively low antenna gain, it is sufficient to rely on geometric accuracy and structural rigidity to compute the phase/magnitude current settings required for beam forming. However, for SSP from a geosynchronous orbit, with a kilometre-scale phased array targeting a terrestrial rectenna from 36,000 km distance, to accuracy within a few metres - something more is required:

3.2. *Retrodirective beam formation & steering*

To transmit a coherent, targeted and focused microwave beam over extended distances, methods utilising a pilot beam emitted from the target have been studied [12]. One such retrodirective technique samples the spherical wavefront impinging on the transmitter phased array, using a system phase reference distributed to all elements across the array. The phase difference between the locally sampled incoming wavefront and this reference is then negated (phase conjugation) and applied to each transmit element at the same or other frequency, so forming the power beam, which converges back to the target.

CASSIOPeiA uses this technique, incorporating a novel and proprietary method for system-wide distribution of the reference phase. The pilot and power beams utilise both different frequencies and different polarisations.

Due to the directional information inherent in the pilot beam wavefront (in conjunction with the distributed reference phase), the computational power required at each element is minimal.

3.3. *Simplified concentrating optical subsystem*

The MSC concept uses a pair of concentrating primary reflectors above/below the orbital plane, angled ~45° to the Sun such that the incoming rays converge towards a secondary pair of (typically) planar reflectors, also angled at 45°, that redirect these rays to converge towards the PV-side of the Earth-facing sandwich panel. The primary reflectors are thus Sun-referenced (rotating once per year), whereas the secondary reflectors and sandwich panel are Earth referenced (once per orbit). This non-imaging optical arrangement is configured to provide uniform, or Gaussian tapered, illumination across the plane of the sandwich panel.

The concentration factor for the MSC is limited to around 3-suns, in order to keep the PV and RF arrays within their thermal limits - necessary to achieve operational lifetime. This is complicated by sunlight impinging directly on the panel at local (ground-track) noon and midnight, the latter case providing no additional photovoltaic conversion and potentially the greatest heat load for the microwave phased array. A system designed-for and operating near optimum peak temperature will thus deliver variable output during the orbital period.

CASSIOPeiA has PV distributed across multiple layers (Fig. 6) – the same substrate as used for the helical phased array, so minimising the structural mass and distribution losses in a similar manner to a sandwich panel. However, having PV across multiple layers prohibits using simple paraboloid concentrating (primary) reflectors, as this would lead to non-uniform illumination across the whole array. Instead, CASSIOPeiA should be illuminated with a collimated source. This offers several advantages:

Unlike sandwich panels, the substrate layers are arranged parallel to the ecliptic plane (edge-on to the Sun), such that the helical arrangement has circular PV apertures available from both ecliptic-north and south (i.e. both sides). Thus 2-sun system insolation is achieved using simple, rigid dual planar reflectors set at 45°, which maintain the solar collimation due to 1AU distance.

Beyond 2-sun concentration, collimation could be achieved with a Cassegrain configuration having paraboloid concave and convex reflectors aligned with a common focal point. A tertiary planar reflector is then necessary to achieve the 90° redirection – which would add mass and increase reflection losses. It is possible to achieve a concentrated, collimated and 90° redirected beam with two reflectors, but these must be pre-distorted to prevent skewed uniformity across the beam. All such solutions require a fixed arrangement of primary and secondary reflectors, so are not available across a rotating frame, such as with the MSC or SPS-ALPHA.

One particular solution is preferential, as it involves linear-variable curvature (i.e. conic) only about one axis. This enables reflectors to be constructed from large area flat film material under uniform tension, whereas paraboloid solutions must have either continuous 2-axis curvature, or be tiled from smaller planar modules having imperfect tessellation (if such modules are identical).

The Solid-State Symmetrical Concentrator (SSSC, Fig. 7, patent applied for) has been modelled with 4-sun (dual ×2) concentration, implemented as a symmetrical pair of primary concave-conic plus secondary convex-conic reflectors. This subsystem produces uniform illumination intensity both across individual layers and at all layer depths (for both sides).

3.4. *Attitude control*

CASSIOPeiA maintains a constant and optimal attitude to the Sun. Having a rotationally symmetric mass distribution minimises microgravity torsional effects – the same gravity gradient (GG) effects used by other concepts to help stabilise their Earth-facing subsystems. With these other systems, any disturbance must be actively damped to prevent pendulum oscillation, typically (in existing satellites) by the use of momentum wheels and small attitude control thrusters.

At large scales, solar photon pressure is one such disturbance which must be accounted for, particularly for structures presenting a variable aperture towards the Sun throughout the orbit – such as GG-stabilised sandwich panels (or other phased array panel).

With CASSIOPeiA, the dual, symmetrical planar or concentrating

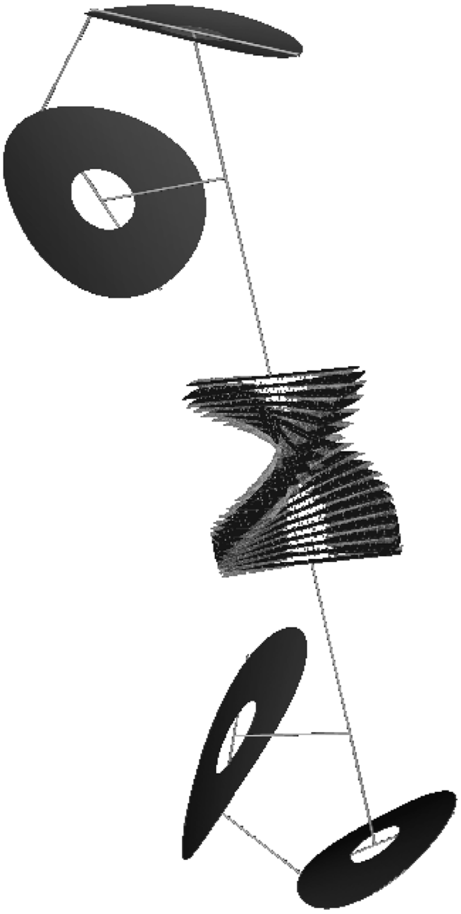

Fig. 7. Solid-state symmetrical concentrator (4-sun).

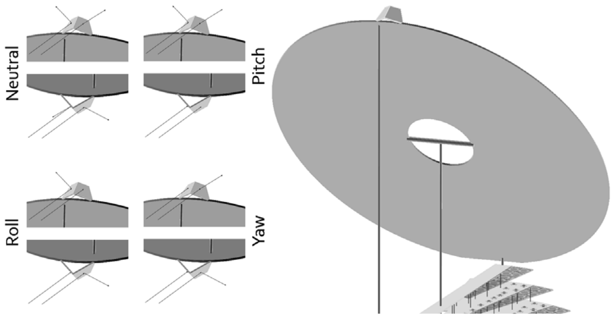

Fig. 8. Full planar reflector (2-sun), with detail of electrochromic attitude control.

conic reflectors are rigid with respect to the helical body. Arranging a small (in-proportion) additional sun-facing reflective area forward of the system centre of mass provides passive stability; any angular misalignment error tends to be corrected by the restoring torque generated by the momentum of deflected photons. By itself, this would not prevent oscillation, but, by overlaying these reflectors with electrochromic material – such as the liquid crystal devices demonstrated on the IKAROS satellite [13], propellentless active damping can be achieved whilst maintaining the satellite's solid-state characteristic. Fig. 8 details four such (slightly tilted) reflector panels providing 3-axis control.

3.5. High concentration photovoltaics

It has long been recognised that the highest PV efficiency can be achieved only at high concentration, utilising multiple overlapping absorption bands. The current record (Dec 2014-) is held by Fraunhofer-ISE/Soitec/CEA-Leti with their quad-junction III-IV cell achieving 46% efficiency at 508 suns.

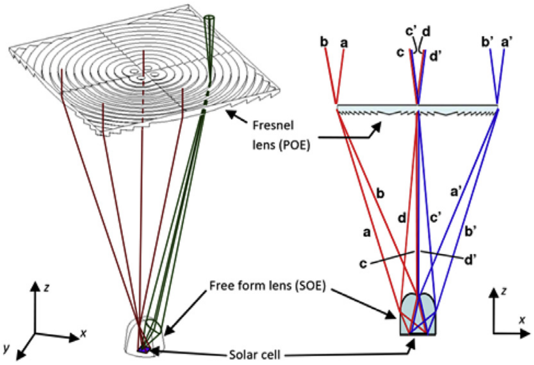

Fig. 9. Fresnel-Köhler (F–K) concentrator – LPI LLC.

Commercial products (including space-rated, high-TRL) are available which achieve $>$ 40% efficiency under high concentration and at temperatures typical of their expected thermal environment ($<$ 100 °C).

Although h-CPV is currently an expensive process using rare elements, this is offset by a reduction in the material area required - equal to the geometric concentration factor.

Utilising a 625-sun Fresnel-Köhler (F—K) configuration (Fig. 9, LPI Corporation [14]) with sub-millimetre scale CPV chip illuminated at $70\,\mathrm{W/cm^2}$, the combined areal mass is far below that of 1-sun PV with protective cover glass - providing an overwhelming advantage in specific power (Fig. 10).

CPV non-imaging optics must trade acceptance angle for concentration factor, with the ×625 F—K example allowing ± 1.3° optical misalignment (less the ± 0.265° solar subtended angle at 1AU). In combination with the SSSC conic reflectors (4-sun system insolation), the F—K geometric concentration is reduced, so-as to maintain the $70\,\mathrm{W/cm^2}$ CPV irradiance. This increases the local acceptance angle, but the overall system pointing accuracy has to improve slightly, in accordance with etendue conservation.

It should be noted that the advantages of h-CPV are not readily available to other sandwich panel concepts (such as MSC and SPS-ALPHA), nor to other single-axis concepts (such as MRJ) in non-ecliptic orbits:

i) Concepts utilising GG stabilisation require symmetry about their long (Earth-pointing) axis to cancel microgravity and photon-pressure torques. Maintaining a rotation-axis normal to the ecliptic from non-ecliptic orbits would likely break this symmetry.
ii) Collimation for h-CPV acceptance angle would require active, continually varying distortion of both primary and secondary paraboloid reflectors to limit skewed uniformity across the CPV

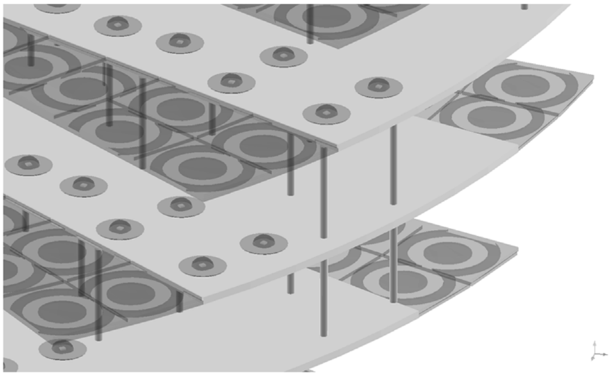

Fig. 10. F-K CPV integrated with the phased array.

array.

iii) Secondary, collimating reflectors have to lie entirely within the projected PV aperture – which is not the case for SPS-ALPHA.

iv) An optimised microwave phased array (elements spaced > ½λ) requires additional mechanical pointing - further complicating sandwich PV optical alignment.

To-date, terrestrial h-CPV has not achieved much market share, compared with silicon and thin-film PV solutions. The narrow acceptance angle of h-CPV requires two-axis solar tracking and high direct normal irradiance, typically found only in low-dust and low humidity desert conditions.

With the approximately doubled efficiency of III-IV h-CPV compared with c-Si PV in such locations, it may be expected that a given land area could produce twice the mean power. However, for east-west tracking through 120° (8 h/day), say, this would require CPV panels to be spaced at twice the panel width to avoid daily self-shadowing. For 150° tracking (10 h) this would increase to almost 4-times panel width. This is in addition to the north/south spacing typical of all large-scale PV farms, according to latitude and season.

3.6. Power and thermal considerations

Due to the collimating optics, incident solar power is uniform across all CASSIOPeiA variants. Additional 1-sun direct heating is assumed negligible in comparison, since the substrate layers are very thin in relation to their spacing (< 1:20) and oriented edge-on to the Sun. Assuming adequate thermal conductivity and emissivity approaching black-body, then by calculating the mean black-sky field of view for the local substrate unit surface area (at a given radius from the CASSIOPeiA twist axis), the mean temperature at points across the CASSIOPeiA body can be found by applying the Stefan Boltzmann equation:

$$\frac{P}{A} = \sigma \times T^4 \qquad [2]$$

where P the incident power (W), A is the total surface area (m^2), T is the kelvin temperature and σ is the Stefan-Boltzmann constant = 5.6703 X 10^{-8} W/m^2K [4].

After considering the refrigerative effect of microwave beaming, the worst-case mean temperature can be found when close to the maximum radius. This works out at ~70 °C for 2-sun insolation and ~90 °C for the 4-sun case. It should be noted that the triple antennae associated with each element receive 1-sun direct insolation and perhaps should be accounted for in the thermal modelling. However, these also have a wide radiative field of view and, taken in isolation, would have a mean temperature between 30 and 40 °C. The exposed antennae thus have a small net system cooling effect (which can be ignored).

The local F—K optics concentrate the system insolation onto a millimetre-scale h-CPV chip at ~70 W/cm^2, irrespective whether planar or concentrating reflectors are in use. Modelling and supplier data have shown that mounting the chip on a heat-spreading radiative copper disk (same flex-circuit copper foil as used for the electrical interconnect), measuring < 8 mm diameter and 18 μm thickness, is sufficient to maintain the photovoltaic chip temperature within normal operating limits at 86 °C (2-sun) or 98° (4-sun), with conversion efficiencies of 40% and 39% respectively.

4. Breaking the non-scaling paradigm

The argument that SSP systems cannot be economically viable below gigawatt levels flows from the following chain of reasoning:

i) GEO is a very good location for SPS, for the same reasons that benefit communications satellites; they rarely enter Earth's shadow – offering 24-h availability, they maintain an essentially fixed position in the sky and the transmit antenna can maintain a fixed, Earth-facing orientation throughout the orbit. Multiple ground-segments remain in view of the SPS – potentially enabling dispatchable power.

ii) 2.45 GHz and 5.8 GHz are two good candidates for beaming frequency; both are Industrial/Scientific/Medical (ISM) band and sit within a low-loss atmospheric window, not subject to interruption by weather. Both offer good RF:DC conversion efficiency (> 90% @ 2.45 GHz) with present-day technology.

iii) From GEO, diffraction physics at these frequencies dictates a massive kilometre-scale space-segment transmit antenna, in order that the ground-segment beam spot (the Airy disk containing 84% of total beam power), and hence rectenna size, is only a few kilometres diameter. This is independent of power level.

iv) System costs are dominated by launch costs, hence by the mass of the space segment.

v) Justification of costs requires highest delivered power, within technical and safety constraints. Given the necessary size of the rectenna, a safe peak beam intensity of < 1 kW/m^2 (230 W/m^2 typical) allows multi-gigawatt delivery – hence multi-gigawatt systems are dictated by economics.

Reasons ii) to v) mostly stand; it is reason i) which offers the most potential for breaking the SSP non-scaling economic paradigm:

There exist alternative, closer orbits where a small constellation of SPS's may provide near-baseload power delivery, together with high utilisation of each satellite in the constellation.

Given a shorter beaming distance, the optimum economic beam intensity (230 W/m^2, say) can be achieved with a smaller, less massive SPS delivering proportionally less power. In addition, the reduced Δ-v required to reach such orbits results in lower per-kilogram launch costs, i.e. the same vehicle can deliver more functional payload mass.

In order to maintain maximum contact time between the ground and space segments, a closer orbit necessarily entails dynamically steering the beam through a far wider angle than is necessary from GEO.

For a planar phased array, this requires a dense arrangement of elements to achieve up to ± 45° of steering without grating lobes. However, once the beam is steered off boresight (defined as 0°), the effective aperture of the planar antenna is reduced by the cosine of the steering angle. This causes de-focussing along the direction of the orbital path. This may require mechanical steering of the antenna array – usually the most massive (having highest angular inertia) part of the system – which may incur delays in handover from one SPS to another as each moves out of range of a particular ground segment and the SPS antenna must be mechanically steered towards the next ground segment. Additional time would then be required to damp system oscillations before beaming could recommence.

Mechanical slewing of a sandwich panel also adds significant complexity to the optical design when having to cope with a variable-tilt focal plane. In practise, a SPS designed for GEO operation may not have a dense (~½λ) element spacing and would be ill-suited to other orbits.

By contrast, dense element spacing is fundamental to the CASSIOPeiA concept; the 360° azimuth steering (without any boresight direction) means there is no azimuthal aperture cosine loss to consider. The fixed attitude maintained between the Sun, (concentrating) reflectors and helical substrate layers means no optical realignment is necessary when switching targets. Ground segment handover times will thus be dominated by light speed signalling delays measured in milliseconds.

4.1. Geosynchronous laplace plane (GLP)

Although no closer than GEO, with an analemma ("figure-8") ground track requiring continuous beam steering, a GLP orbit offers distinct advantages:

Table 2
GLP orbital variants.

GLP Orbit: CASSIOPeiA Variants			
System Insolation	Reflector Type	Power (MW_{AC})	Mass (T)
1-sun	Planar (quadrant)	1070	1350
2-sun	Planar (full)	1470	1770
4-sun	SSSC	2050	2010

Geostationary satellites require around 50 m/s Δ-v correction per year to maintain station-keeping in the presence of perturbations; principally lunar and solar gravitational effects. A high area-to-mass ratio satellite such as an SPS also has to contend with photon pressure effects, causing sub-year changes in eccentricity, which interacts to cause significant inclination and other drift.

It is often assumed that a SPS will require regular servicing to replace worn components and refresh station-keeping propellent. To-date, there is no infrastructure available to service GEO satellites - though it is currently in development.

Laplace plane orbits are highly resilient to perturbation, requiring minimal (if any) station-keeping propellent [15]. The precise orbital inclination (7.7°–8.7°) can be chosen according to the SPS's Sun-facing area/mass ratio, minimising the effects of photon pressure and placing the system onto a "frozen" orbit. CASSIOPeiA's lack of mechanical wearing parts and sub-wavelength modularity allows the system to be designed for graceful degradation over its operational lifetime (assumed 20 + years) without planned maintenance – leading to low operational costs. Table 2 shows three CASSIOPeiA variants for GLP orbits.

4.2. Equatorial medium earth orbits (MEO)

With a typical beaming distance of 24,000 km (to 40°N latitude) and ~12-h orbital period, four satellites could provide near-baseload power (> 92% utilisation, > 22 h/day) to four rectenna sites around the globe.

Fig. 11 shows such simultaneous coverage optimised for Xi'an, Rome, New York City and Hawaii.

Table 3
MEO orbital variants.

MEO Orbit: CASSIOPeiA Variants			
System Insolation	Reflector Type	Power (MW_{AC})	Mass (T)
1-sun	Planar (quadrant)	688	866
2-sun	Planar (full)	974	1020
4-sun	SSSC	1310	1280

An optimum peak beam intensity of 230 W/m^2 is met with CASSIOPeiA scaled as shown in Table 3. Each variant would require elliptical rectenna sites at ~2,000ha (5000 acres) per gigawatt.

4.3. Elliptical sun-synchronous orbits

At 116.6° inclination, a retrograde 3-h elliptical orbit precesses to maintain a fixed orientation of the orbital plane with respect to the Sun throughout the year. Due to the eccentricity, satellites experience an extended loiter period above the northern hemisphere.

Any GG-stabilised SPS concept (including MRJ, MSC and SPS-ALPHA) would be unable to maintain its Earth-pointing axis in such a Highly-Elliptical Orbit (HEO); the system moment of inertia is too high to match the variable orbital angular velocity dictated by Kepler's second law. In contrast, CASSIOPeiA can adjust its Sun-facing roll attitude and fixed planar reflector angles for optimum HEO beam steering throughout the year.

A five-SPS constellation, with ascending nodes spaced 72° apart, can deliver power with near-baseload utilisation to three rectenna sites, e.g. Beijing: 96% (23 hrs 1 min), San Francisco: 86% (20 hrs 40 mins) and Glasgow, UK: 78% (18 hrs 42 mins), each satellite thus averaging 52% utilisation.

Challenges include rectenna elevation angles down to 15° and a reduced life due to Van Allen belt radiation.

Optimised for peak intensity at 1-sun (@ 2.45 GHz), each satellite would mass 266 T and deliver 211 MW to the rectennae, however, by further down-scaling to match the payload capability of the latest BFR/BFS (100 T with LEO refuelling), this would allow an entry-level baseload SSP project at much-reduced cost (~$1.5 B for the 5-SPS

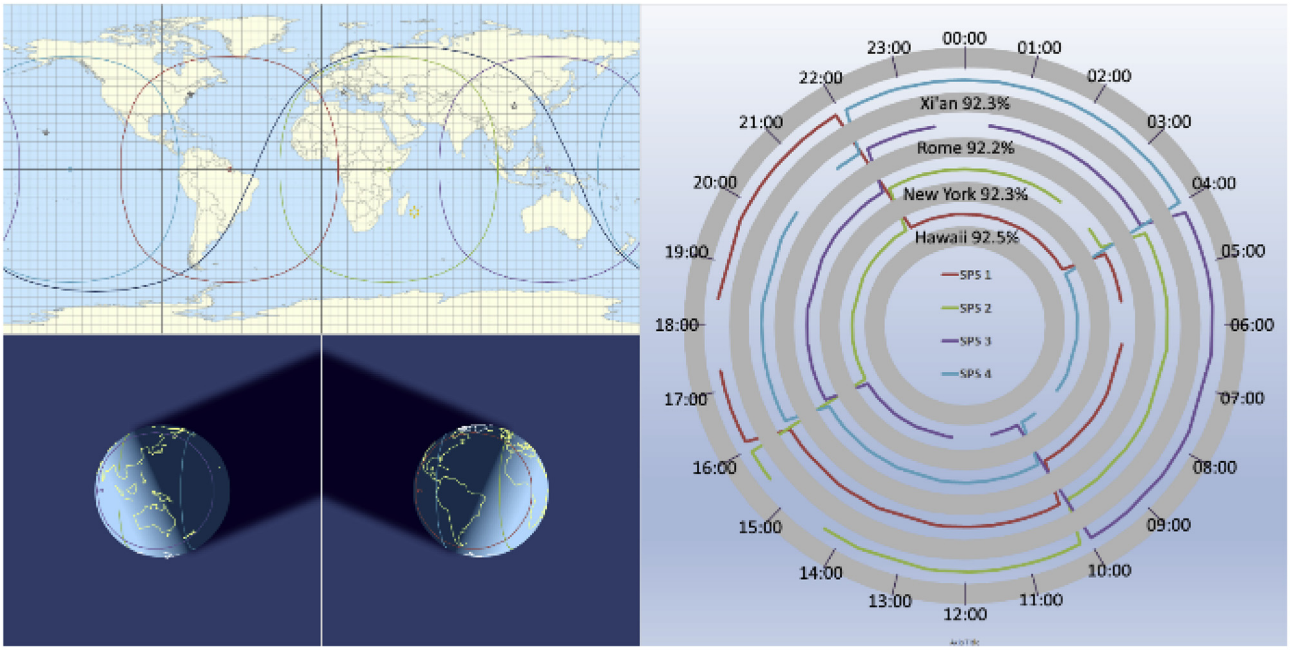

Fig. 11. MEO Utilisation; 4 satellite constellation, 4 rectennae.

constellation), shared internationally, without the technological risks of on-orbit robotic assembly.

Although the rectenna sites would need to be oversized (due to the low elevation angles), they would also require only minimal refit when upgraded for higher power MEO and GLP systems.

4.4. *LEO applications*

While LEO is a poor choice for power beaming to Earth (minimal rectenna contact time, SPS eclipsed approximately every 90 min), CASSIOPeiA opens new opportunities for small satellites in both power beaming and non-power beaming applications.

By eliminating the requirement for mechanical antenna pointing, the satellite has freedom to maintain optimum attitude for accomplishing its primary mission:

4.5. *Earth observation (EO)*

An EO satellite is able to point its telescope to the desired target, whilst communicating to a different Earth-bound or orbital platform.

Some existing satellites utilise 2-axis mechanical steering of microwave horn antennae for this purpose, but this reduces reliability and may cause attitude control and/or vibration issues.

4.6. *SkimSats*

SkimSats [16] are Very-Low Earth Orbiting (VLEO) platforms which must maintain a streamlined attitude to minimise atmospheric drag. As such, they only have one degree of freedom – rotation about an axis tangential to the orbit. CASSIOPeiA could provide a single antenna solution for comms/RADAR in any direction.

4.7. *Swarm robotics*

Current satellites only have access to power proportional to their PV area, plus that available through on-board batteries.

A small-scale CASSIOPeiA (0.5–10 m diameter) could form the hub of a free-flying cluster of small robots, each with access to power far exceeding their size, over distances of up to a few hundred metres, e.g. to power ion-thrusters, electromechanical manipulators, etc. The ability to change beaming direction at electronic speed enables power multiplexing for a potentially large number of robots.

Applications for such a cluster would include orbital assembly and space debris removal. A continuous, terrestrial, power transfer demonstration to a circling aerial drone is now in development.

4.8. *Stratospheric deployment*

As a precursor to space-launched solar power, the CASSIOPeiA antenna could be mounted within an autonomous blimp, station-keeping at ~20 km altitude within the stratosphere. At 34 metres [17] (5.8 GHz) or 50 m (2.45 GHz) diameter, with high efficiency PV (e.g. perovskite) on the outer skin, CASSIOPeiA would be able to deliver several hundred kilowatts to a portable 70 m rectenna located anywhere with a 27 km ground radius. At these diameters, it could do so at the same 230 W/m^2 peak beam intensity as intended for space solar.

Whereas other solutions require suspending antennae below the airship, the compact-folding nature of CASSIOPeiA allows residence within the envelope, centred on the roll axis. Multiple pressure-tensioned supporting cables cause deployment upon inflation. Pitch and yaw control are somewhat wind-dependent, but the blimp still has wide freedom for best solar orientation.

Although subject to the diurnal cycle, power would be predictable and reliable from sunrise to sunset, finding applications including emergency relief.

With high commonality and the ability to retrieve and repair, valuable lessons would be directly applicable to later space-launched missions.

5. Conclusion

On the cusp of true reusable space launch, coupled with the highest continuous specific power available from advances in solid-state SPS design, a new and near-unlimited source of low-cost, sustainable baseload power may soon be in reach.

However, this alone may not be sufficient to initiate ambitious development, if the cost of pilot programmes remains at multibillion-dollar levels.

By breaking the non-scaling paradigm, CASSIOPeiA offers a low risk roadmap, able to deliver useful power at every level of implementation.

References

[1] World Energy Council, World Energy Scenarios: Composing Energy Futures to 2050, (2013).
[2] World Nuclear Association, Current and Future Generation: Molten Salt Reactors, (2018).
[3] International Thermonuclear Experimental Reactor, www.iter.org.
[4] NeoEn Hornsdale Power Reserve (Tesla): hornsdalepowerreserve.Com.au.
[5] SunPower Solar Star PV Farm: us.sunpower.com/utility-scale-solar-power-plants/.
[6] NASA, 1979, Satellite Power System, Reference System Report DOE/ER-0023.
[7] Space Exploration Technologies: www.spacex.com/about/capabilities.
[8] Energy Information Administration, US, www.eia.gov/forecasts/aeo/electricity_generation.cfm.
[9] Chinese Academy of Space Technology, Multi-rotary joints SPS: spacejournal.ohio.edu/app/generic.html.
[10] J.C. Mankins, http://space.nss.org/media/NSS-JOURNAL-New-Developments-in-Space-Solar-Power.pdf, (2017).
[11] I. Cash, www.mtu.edu/ece/department/faculty/full-time/zekavat/pdfs/ssp-2017/ssp2017-cassiopeia-sica-design-presentation.pdf, (2017).
[12] JAXA research and development directorate, http://www.kenkai.jaxa.jp/eng/research/ssps/hmi-mssps.html.
[13] JAXA, Successful Attitude Control by LCD, (2010) http://global.jaxa.jp/press/2010/07/20100723_ikaros_e.html.
[14] LPI Corporation, (2010) lpi-llc.com/Papers/FresnelPVConcentrator.pdf.
[15] I.J. McNally, Orbital and Rotational Dynamics of Solar Power Satellites in Geosynchronous Orbits, (2018).
[16] A. Bacon, data.satirg.org/wp-content/uploads/2015/11/IET-2014-Low-cost-Satellite-comms-approaches-utilising-Skimsats-and-OmniSats.pdf, (2014).
[17] Thales Alenia Space, (2018) www.thalesgroup.com/en/taxonomy/term/7436.