Chapter 4
How Will Sunsats Be Delivered to Space?

Abstract This chapter outlines several approaches to delivering powersats into low, medium, geosynchronous, Sun-synchronous and other space orbits. A historical context is given and next-generation launch strategies are introduced. Increased spacecraft size, mass and deployment frequency of payloads and deployment are among the challenges discussed.

Launching Sunsats

As with communications satellites, solar power satellites must be lifted from Earth and delivered into designated orbits. Some will be positioned quite near Earth, while others will be farther away. To place any satellite in space for the purpose of relaying energy to the ground, providers of these services must go through a prior approval process with the International Telecommunications Union and other oversight authorities.

The more promising locations for directing power to Earth appear to be in LEO at roughly 300 km, in the geosynchronous Earth orbit (GEO) at 36,000 km or in an elliptical orbit that will permit always-in-the-Sun reception. Some strategists propose using space-to-space energy reflectors to relay power from satellites gathering the Sun's rays in daylight, transferring power to satellites orbiting in the shadow of Earth from where the beam will be down-linked to ground antennas.

Others look to the Moon as a future base for collecting and beaming solar power to Earth. Such an energy source could be used as well for the electric propulsion of spacecraft into deeper space. Among the more innovative Sunsat architectures are those that network multiple solar power satellites, treating them as a single photovoltaic mass serving one or more than one world region.

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An Historical Perspective

Space engineer Ralph Nansen has spent much of his career designing, developing and advocating concepts that relate to space solar power. Starting as a designer on the Bomarc rocket-powered missile for the Boeing Company, Nansen was selected in 1961 to design the configuration used by Boeing in building the giant first stage of the Saturn V Moon rocket. In 1962, he became design manager of the Saturn S-1C fuel tanks, the first stage of the rocket that propelled the *Apollo* astronauts to the Moon.

From 1975 to 1980, Nansen served as Boeing solar power satellite program manager. He gathered the team of engineers, scientists and associate contractors that developed the overall SPS concept under the auspices of the Department of Energy and NASA. He presented numerous papers and participated in international conferences on future space projects in Germany and Egypt. He was invited to China as a member of the first Space Technology Exchange Mission in 1979. Nansen was asked to testify before such Congressional committees as the Senate Space Subcommittee in 1976 and the House Subcommittee on Space and Aeronautics in 1978 and again in September 2000.

From 1985 to 1987, he was responsible for developing the design proposal for a fully reusable horizontal take-off space transportation system and the structural design of Boeing's National Aerospace Plane concept. Nansen retired from Boeing in 1987 and has since written two books on the world energy crisis and potential solutions from space.

Nansen says the barrier to SPS development is the lack of a low-cost space transportation system for launching the satellite hardware. "Without a reusable launch system there is little hope of deploying a significant capability to generate competitive cost electric energy from space. The problem is not technology; it is the up-front investment money and understanding of what is required" (Nansen 2010).

In his article for the *Online Journal of Space Communication* on the topic of low cost access to space, Nansen focuses on the specifics of developing a space transportation system based on reusable vehicles, an approach that he is confident will finally make solar power satellite deployment commercially viable. The first step, he writes, "is to look at what has occurred in the past and see what has happened, and why it happened. To make the right choices for the future… we need to understand what is different now." He continues:

> All of the early launch systems starting with the launch vehicle for *Sputnik* were expendable rockets. In the early days, there wasn't much choice. To reach orbit, launch systems had to be made as light as possible to achieve orbital velocity. There was nothing left over for adding recovery systems that would allow reuse. As time went on, systems got more efficient, but overall program cost became a key decision maker. To minimize cost, payload was reduced. The added cost of development for a reusable system was traded against the number of flights required. The other element was that many of the payloads needed to go to high orbits that made the recovery of the upper stages difficult and costly. As a result, the market was not large enough to justify the cost of a reusable system. The optimum manageable design was always to build a highly efficient expendable system. Once the commercial satellite providers managed to become profitable using expendable rockets, the launch vehicle builders had no real incentive to develop reusable systems (Nansen 2010).

"As the Saturn/Apollo Program was winding down," Nansen writes, "NASA stepped forward with a bold plan that could have led to a new era of space development. It was the plan for a space shuttle. NASA's criterion was for a fully reusable two-stage winged vehicle that would burn liquid hydrogen and oxygen as the propellants in both stages." The big constraint, he says, was the level of technology available in 1970. The two biggest stumbling blocks were (1) the maximum gross liftoff weight and (2) the need to use hydrogen as the booster fuel. Hydrogen fuel use dictated a much larger vehicle than would be required with a hydrocarbon fuel booster. The gross lift-off criterion was incompatible with hydrocarbon fuel and the size of a hydrogen fueled booster. None of the bidding contractors could meet the liftoff criteria.

"Now close to 40 years later," he writes, "the United States has had two fatal accidents on space shuttle flights, each mission costs a small fortune to fly, and now the entire fleet is slated to be retired…. The question is: What can we do today to develop a reusable space transportation system with a minimum of developmental costs?"

Nansen's recommendation is "to reach back 40 years to the technology we understand, update it with modern knowledge and materials and incorporate what is learned into a fully reusable vehicle that applies the known principles of low cost transportation systems. Those principles are high usage, low maintenance, reasonably sized payloads, and ease of loading and unloading. When a transportation system reaches maturity with these characteristics, the cost of operating the system can be expected to be between three and five times the cost of fuel. With today's systems, the cost is over a thousand times" (Nansen 2010).

With the development of a fully reusable launch vehicle designed for commercial use by people who understand commercial operations, Nansen believes that solar power satellite hardware can be launched at a low enough cost that the satellites will provide competitively priced electricity to Earth. "Such an event would be the beginning of the new era of energy from space that would bring economic growth to the world while at the same time stopping the addition of carbon dioxide to our atmosphere" (Nansen 2010).

Launch Strategies

It can be assumed that any solar power satellites built today will be launched on the same private, commercial and government rockets used by the comsat industry to lift their communications satellites. It can also be assumed that, as cheaper and more suitable launch options appear, both Sunsat and comsat clients will benefit.

Forty or more years of practice has led to a high level of confidence in the launch industry's capability to deliver spacecraft into orbits of choice, using a range of launch vehicles to accommodate quite specialized payloads. The prospect of a new generation of satellites pursuing a new business category—that is, providing a continuous supply of clean and abundant energy to all countries—will give the launch industry the spurt of growth it has been hoping to see. Launching solar power satellites will be its first

Fig. 4.1 The Falcon heavy launch vehicle of Space Exploration Technologies is to be launched at Cape Canaveral in 2014. The rocket will lift satellites and cargo weighing 53 t into low Earth orbit at 200 km (SpaceX 2011)

opportunity to demonstrate that it can provide not only safe and reliable transport to space, but also can deliver it in sufficient volume and at sufficiently low cost to ensure the worldwide availability of competitively priced electricity (Fig. 4.1).

Bruce Elbert, in his widely used *Introduction to Satellite Communication*, points out that the three most common criteria in launch vehicle selection relate to launch mass capability, the reliability or success record of the system and the cost of use (Elbert 1999, p. 406). Spacecraft are normally designed for compatibility with a particular launch vehicle to be placed into a specified orbit. The place where a spacecraft is launched, whether on land, sea or in the air, will very much depend on its ultimate destination. For example, a GEO placement in space will prompt a launch location closest to the equator, since the highly desired GEO orbit is 36,000 km above Earth's equator. For a spacecraft with a non-GEO destination, launch will likely occur from a site located at some higher latitude.

"The sequence of steps that begin when a spacecraft aboard its launch vehicle leaves the launch platform and concludes when the spacecraft is separated in space is called the launch mission. In some cases the launch mission is completed short of the actual orbital destination when, for reasons of cost or complexity, the spacecraft is unloaded and caused to continue to the designated altitude and position using its own power. This is most often the case with GEO satellites, when the launch vehicle places its payload into a geo-transfer orbit (GTO). In other cases, the launch vehicle accompanies the payload the entire distance" (Elbert 1999, p. 406).

Fig. 4.2 China's powerful Long March-5 rocket in development will sport engines with the thrust of 120 t, with a test launch scheduled for 2014 (Zak 2010)

Some plans involve assembling solar satellites and their antennas from components lifted by medium power rockets into LEO, possibly using the International Space Station or other space platform as a staging area, later transferring them into their final position in a geosynchronous or other orbit. Other plans include inserting the solar spacecraft and its large arrays directly into orbit using more powerful and agile thrusters (Fig. 4.2).

Reducing Costs

Phillip Chapman, an Australian-born geophysicist and astronautical engineer who served as a scientist-astronaut for NASA during the Apollo era, wrote about economical launch vehicles, energy and environmental policy and space solar power in Issue No. 16 of the *Online Journal of Space Communication*. Giving thought to the cost of launching solar power satellites and incorporating launch technologies available today, he concluded that the cost of spaceflight is not a serious impediment to realizing the advantages of power from space.

"It is important to recognize that spaceflight is not intrinsically expensive," Chapman notes. "The energy needed to place a payload in LEO is ~12 kWh/kg.

If it were possible to buy this energy in the form of electricity at U.S. residential prices, the cost would be <$1.30/kg. Rockets are very inefficient, but the cost of the propellants needed to reach orbit is typically <$25/kg of payload.

"The principal reason that launch to LEO is currently so expensive (>$10,000/kg) is that launches are infrequent—and they are infrequent because they are so expensive. Launch vehicles (LVs) are costly to build because the production volume is low; each LV is thrown away after one use. Annualized range costs are shared among just a few launches, and the staff members needed for LV construction and launch operations are grossly underemployed. The quoted prices for launch would be much higher still were it not that in most cases the Department of Defense or NASA has absorbed the LV development cost" (Chapman 2010).

He calculates that economies of scale in any significant space-based solar power (SBSP) program will permit launch at acceptable cost, even without major advances in launch technology. "To be definite, a fairly modest SunSat deployment program is assumed, with the first launch taking place in 2015, leading to an installed SunSat capacity of 800 gwe in 2050. This goal will represent somewhere between 6% and 9% of the total global capacity that we will need by then" (Chapman 2010).

Chapman's analysis uses simple standard models to approximate the performance and cost of LVs, with subsystem characteristics comparable to those of existing engines and vehicles. "The only major technical innovation considered," he writes, "is the introduction of reusable LV stages, and the only major change in spaceflight practice is launch from an equatorial site." There was no attempt, he states, to optimize the launch architecture, although improved designs and advanced technologies would offer significantly lower costs (Chapman 2010).

The principal problems in closing the business case for a launch services provider that supports space-based solar power, he says, are related to financing the venture rather than the cost of operations or the eventual profitability. For example, he notes: "[A] launch price of $450/kg leads to a maximum deficit of $60 billion in the 12th year of the deployment schedule, and the cumulative cash flow does not become positive until the 22nd year—but the end result in 2050 is a profit of $180 billion (Chapman 2010).

"The delay in profitability exceeds the planning horizon of most venture capitalists, so the project probably requires both a strong government commitment to completing the deployment as well as some form of financial guarantee. Creative financing could help; for example, the launch price could be set at $600/kg in the early years, with a contractual obligation to refund some of the money once the cash flow went positive" (Chapman 2010).

Chapman isn't recommending a particular design for RLVs; rather, in this paper, his purpose was "to show by example that the cost of launch to LEO is not a reason to delay implementation of SBSP as a major contributor to energy supply in the United States and around the world. The need is urgent, and the best time to begin a serious development program is right now" (Chapman 2010).

Gordon Woodcock, honored in 2011 by the National Space Society for distinguished service in advancing the case for space-based solar power, has addressed the topic of launch costs on multiple occasions. He calls launch costs "The Big Show-Stopper" (Woodcock 2010, p. 1).

In a presentation at the 2010 International Space Development Conference in Chicago, Woodcock concluded that re-usable systems can deliver acceptable costs if (1) there is high demand; (2) these systems have long life; (3) there is a short turnaround time; and (4) they have modest turnaround cost. His analysis shows fully reusable vehicles are not worth the investment unless demand is at least 50–100 launches per year, and that the turnaround is less than a week on the ground between flights.

For getting started, he said, investment analysis shows a partially reusable heavy lift vehicle with flyback booster can be justified at 3–5 launches per year or more (when there are additional purposes for such missions as human space exploration). He assumes that the smaller, fully reusable passenger vehicles for space tourism to orbit are helpful steps along the way (Woodcock 2010, p. 3).

Reusable Rockets

The National Space Society gave its Space Pioneer Award for Business Entrepreneur to SpaceX in 2011, in recognition of its successful launch of two Falcon 9 rockets and the safe return of its *Dragon* capsule. NSS Executive Committee Chair Mark Hopkins noted, “The high cost of launch has always hampered the exploration and development of space. With its Falcon Heavy vehicle, SpaceX seeks to achieve a major reduction in launch costs. Such a reduction could enable entirely new categories of space industry” (Hopkins 2011).

SpaceX CEO Elon Musk announced in April 2011 that the company had scheduled two or three Falcon 9 launches for 2011, with launch rates ramping up to five or six in 2012, growing to 12 per year by 2014. Musk said the company’s goal is to launch this vehicle 20 times per year, a rate that would permit SpaceX to further reduce per-launch charges (de Selding 2011).

Musk said the company’s Falcon 9 rockets would be entering into competition with the Atlas 5 and Delta 4s for U.S. Air Force contracts, but would also compete with the Russian Proton and the European Arianes in the commercial marketplace. When measured in terms of the cost of placing a given satellite into orbit, he said, the Falcon 9 Heavy would be only half as expensive as the Russian Proton (de Selding 2011).

NASA spokesperson Lori Garver was quoted in a *Space News* article as saying that a conventional NASA procurement of its own heavy-lift rocket, including its first flight, would cost nearly $4.5 billion. Outsourcing development to SpaceX, she said, would cut that figure by 60%, but only if other customers purchased the vehicle, permitting scale economies to reach maximum effect (de Selding 2011).

China’s launch industry will feel the impact of these developments as well. According to *Aviation Week & Space Technology* editor Frank Morring, “Executives at China Great Wall Industry Corp. find it hard to believe that U.S. Space Exploration Technologies, Inc. (SpaceX) is offering lower launch prices than they can. But they concede privately that it’s true.”

Morring goes on to explain, "China Great Wall, the marketing arm of China Aerospace Science and Technology Corp. (CAST), is opening a one-person office in Washington, DC this summer to push Chinese space products, including solar arrays. Chinese officials say they find the published prices on the SpaceX website very low for the services offered, and conceded they couldn't match them with the Long March series of vehicles even if the U.S. export-control regulations made it possible for them to loft satellites with U.S. components in them." The SpaceX website has an advertised lift capacity of 10,450 kg for the Falcon 9 payloads from Cape Canaveral for $54 to $59.5 million (Morring 2011, p. 22).

Alternative Approaches

Multiple strategies abound for lifting people and material into space more efficiently, more often and less expensively. One of the less talked about strategies is to use highly focused laser or microwave power to lift satellite vehicles, their parts or payloads into LEO; another is the related space elevator. A common version of the space elevator involves connecting a high strength ribbon (a carbon nanotube tether) from a space satellite to an offshore sea platform. Mechanical lifters attached to the ribbon would be propelled up the ribbon, pushing cargo into space.

Dallas Bienhoff, in a 2008 paper presented to the AIAA, touched on some of these alternative approaches. He wrote:

> From the brute force approach to a more elegant, precisely choreographed and integrated system, the Tether Launch Assist approach can place payloads onto a geosynchronous transfer orbit (GTO) trajectory using a smaller launch vehicle and less than half the upper stage propellant compared to our current rocket/upper stage approach. Development costs for the suborbital RLV are reduced relative to typical RLVs due to the lower delta v requirements for launch and the need for smaller upper stages that perform orbit circularization only. Upper stage capability requirement is reduced as the perigee burn function is provided by the tether. Operationally, the launch vehicle carries the payload to altitude and releases it in time to meet the passing tether payload hook. The tether rotates so the capture hook is traveling in the opposite direction as its center of mass when the payload is snatched to minimize the relative velocity between the RLV and capture hook. After snatching the payload from free space, the tether rotation carries it upward to its release position 180° away. Tether design is such that the release velocity equals the perigee velocity required for the payload to reach its desired apogee. An apogee burn is necessary for final orbit circularization.
>
> Space elevators…may offer the ultimate low-cost access to space. Consisting of an Earth station, a ribbon, a climber and a counterweight beyond GEO, space elevators may be able to place payloads into GEO for about $100/kg. The climber has wheels, or grippers, that squeeze the ribbon and drive the carrier up to GEO. The ribbon extends from a counterweight beyond GEO to an operating platform on the ocean's surface along the equator. Lasers beam energy to photovoltaic cells on the climber, which provides the electricity to power the grippers. Depending on climber speeds, trip time to GEO may take anywhere from 1 to 10 days. [Subsequent climbers] can initiate their ascent as soon as the previous one reaches the altitude where gravity has decreased to 0.1 g. Because space elevator

> ribbons are one-way paths, each elevator site will need two or more ribbons for efficient operations; one for Earth-bound climbers and one or more for space-bound climbers (Bienhoff 2008, p. 8).

A new and plausibly workable approach to Earth-to-space propulsion calls for heating a rocket's propellant by focusing energy on it from ground-based lasers or microwave sources. This concept to "transmit the energy from the ground to the vehicle" was developed in 1991 by Jordin Kare of Kare Technical Consulting. Instead of explosive chemical reactions onboard a rocket, beamed thermal propulsion would launch a rocket by shining laser light or microwaves at it from the ground (Patel 2011, p. 1).

Beamed thermal propulsion systems would involve focusing the beams on a heat exchanger aboard the rocket. The heat exchanger would transfer the radiation's energy to a liquid propellant such as hydrogen, converting it into a hot gas that is pushed out of the nozzle. Proponents suggest that this approach would make possible a reusable single-stage rocket that has 2–5 times more payload space than conventional rockets, dramatically slashing the cost of sending payloads into a low Earth orbit. NASA is now conducting such a study to examine the possibility of using beamed energy propulsion for future space launches.

Kare had calculated that it would take 8–10 min for a laser to put a craft into orbit, while microwaves would do the job in 3–4 min. The vehicle would have to be designed without shiny surfaces that could reflect dangerous beams, and aircraft and satellites would have to be kept out of the beam's path. Such launch systems would be built in high-altitude desert areas, so danger to wildlife would be minimized (Patel 2011, p. 2).

Concluding Thoughts

Launching satellites safely and economically into space is one of many significant challenges facing the satellite industry. Any positive momentum toward cheaper launches will be good news for space energy, space communications and related space businesses. Private/public initiatives to regularize space transport are helping to establish access to space as a viable enterprise in the way that terrestrial aerospace is viable today.

To avoid the high costs of launching people and cargo into space, some visionaries see space-based infrastructures being built from materials found in space, with robotic manufacturing and assembly managed from Earth via virtual communications and control. Although this seems far off, solar power plants operating in near-Earth orbits can be expected to provide a near-term market large enough to stimulate a more diverse space transportation system. These developments mesh well together. With lower cost space transportation, energy from space becomes the go-to source for supplemental (and eventually replacement) power, the volume of which will drive down overall costs.

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