SERVER SKY - Computation in Orbit

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Abstract

It is easier to move bits than atoms or energy. Server-sats are ultra-thin disks of silicon in earth orbit, powered by a large solar cell, propelled and steered by light pressure, networked and located by microwaves, and cooled by black-body radiation. Arrays of thousands of server-sats form redundant computation and database servers, connected by phased array antennas to millions of ground transceivers.

First generation server-sats are 20 centimeters across (about 8 inches), 0.1 millimeters (100 microns) thick, and weigh 7 grams. They can be mass produced with off-the-shelf semiconductor technologies. Radio chips provide intra-array, inter-array, ground communication, and precise location information. Server-sats are launched stacked by the thousands in solid cylinders, shrouded and vibration-isolated inside a traditional satellite bus.

The Computing Energy Crisis

Traditional data centers consume almost 3% of US electrical power, and this fraction doubles every five years [DATA]. Computer technology is improving - new hardware delivers the same computation for half the power of two-year-old hardware. The demand for computation increases more rapidly.

Most computing growth now occurs outside of the United States, in rapidly developing countries such as China. Some estimate that total computing power for the planet doubles every year, implying that world computing energy demand doubles every two. We are not constructing enough clean power plants to meet this rapidly growing demand. Global competition for diminishing fuel supplies may grow deadly in the coming decades. The U.S. may generate less power in 20 years, while data center and communication power grows to 40% of total load.

A likely outcome is power rationing. In the best case, virtualized computers will get smaller and smaller time slices on crowded hosts, increasing response time. While fiber internet to the home is capable of enormous bandwidth, the optical network terminals at the customer end and the switches and routers at the ISP end may be slowed down to reduce power, increasing response time.

Unless we learn from recent history, the actual outcome may be worse. During the California energy crisis, utilities reacted to high demand by shedding customers. Data centers are often powered with battery-backed uninterruptible power supplies, but these systems are limited, expensive, and inefficient. Data centers will shed compute load during blackouts, and go dark during long power outages.

Packets travel through dozens of switches between the data center and the end user. The internet is agile, and can route around failed links, but too many un-powered switches results in inefficient routes, increasing the load on the switches that remain. The result is an increasingly slow, unreliable, and unpredictable internet. As “smart power” grids become increasingly dependent on computing and internet communication to extract maximum efficiency from limited generation, we may get into deadly positive feedback loops, leading to cascading failure of the combined computing and generation grid.

Alternative energy systems such as ground-based solar photovoltaic intercept sunlight that otherwise feeds the biosphere. Generating the world's energy needs (estimated at 40 Terawatts by 2050 [SMAL]) with solar cells requires millions of square miles of solar arrays. The estimated roof area for the entire United States is about 30,000 square miles, and paved area is around 60,000 square miles [AREA]. Covering many times that area with solar collectors will cost more than all our roads and buildings. Most importantly, solar power goes away at night - storing 12 hours worth of electrical generation also requires huge amounts of infrastructure. Terrestrial solar is not a practical way to generate Terawatts of electricity.

The Sun fills space with 360 trillion Terawatts of unused energy. Space solar power satellites [SSPS] may someday capture some of this energy and beam it to earth. SSPS transmit antennas produce intense microwave beams, focused on large "rectennas" on the ground, which converted the power to electricity for the grid. If the satellites are in geosynchronous orbit, the beam-spread at the ground is large, requiring large rectennas.

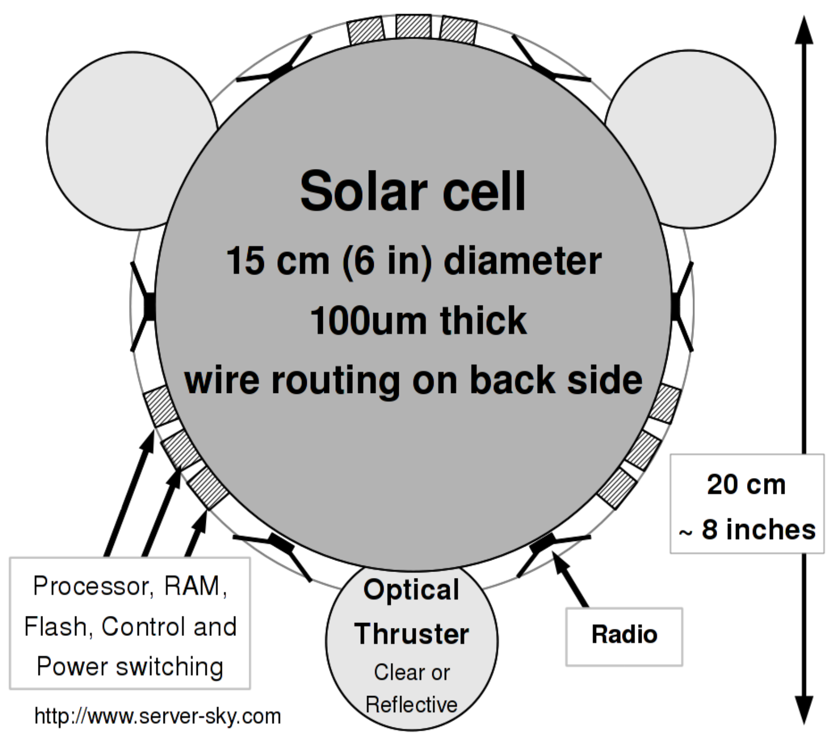
SSPS power could drive data centers. However, the path from orbit to end usage is inefficient, with losses from transmission, side lobes, power conversion, data center cooling, etc. A 20% efficient, one meter square solar cell in orbit intercepts 1300W of sunlight. Of the 260 watts of electricity produced, minus inefficiencies and the energy needed to supply and maintain the SSPS, perhaps 4% reaches the compute load in a data center.

Server Sky

What if the conversion steps between the solar cell and the compute load could be eliminated, and all 260 watts per square meter could be turned into computation? Moving the computer and the data center functions into space eliminates the intermediate steps Solar cells directly produce the high current, low voltage power that a modern CPU needs. The cost-effectiveness of space-generated power goes up by almost 30 times. If the data are radioed to and from points on the Earth, much of the power and resource-consuming communications infrastructure on the ground can be eliminated as well.

Server Sky computes with space solar energy. It strips away the mechanical structure, power transmission and conversion, and large power transmitters of a solar power satellite, so it is cheaper to launch and easier to make.

Server Sky builds many arrays of ultra-thin (100μm) 7 gram satellites. Each "server-sat" maneuvers by light pressure, and converts electricity from a 15cm (6 inch) solar cell directly into computation and radio transceiver power. Server satellites are mass produced by the millions or billions, and are launched in dense stacks with conventional rockets to a 6411 kilometer altitude orbit. The server-sats deploy into large arrays to form phased array radio beams that can address many small spots on the ground. Recent advances in distributed array computing, CMOS radiation resistance, error detection and re-computation, and electro-chromic light shutters allow server-sats to be manufactured cheaply with existing factories, some idled by recent economic troubles. Although expensive to launch, they will be vastly cheaper and more power-efficient than traditional satellites. Server sky infrastructure and power savings quickly pays for launch costs.



Server Satellites

Solar cells, integrated circuits, and interconnect are two-dimensional systems. Modern IC die are thinned to increase thermal conductivity and reduce package height. The target thickness for the first server-sats is 100 microns. 10,000 server-sats are stacked in a solid 1 meter column.

Decreasing server-sat weight reduces launch cost and makes a more effective solar sail. The current thickness target is 100 microns. Production silicon wafers are thinned to as little as 20 microns for some applications. 100 micron thick silicon is flexible, and can be rolled to diameters less than a centimeter without breaking. Future server-sats may become thinner than 10 microns, weighing less than a gram.

Server-sats are uniformly planar, for stacking during launch. The integrated circuit chips are arranged around the edge, and power feeds outwards (in separated zones) from the solar cell. If a portion of the solar cell shorts out or is otherwise damaged, the remaining circuitry still works.

Electronics: Large databases will be distributed over many server-sats. A server-sat used for database or web service may need as much as a terabit of flash memory. That is about 20 cm^2 of silicon area. Computational server-sats need much less. While some high-performance processors and chip-sets use hundreds of watts, Giga-instruction-per-second level machines can get by with far less. For example, the PC Engines ALIX, based on the AMD X86 Geode processor, is a complete 4 watt system (including IO and power conversion losses) with 990 bogo-MIPS performance [ALIX] . Optimized server-sats can do far better.

Because the server-sat is very thin, some common electronic components cannot be used: electrolytic capacitors, cored inductors, etc. Components such as crystals for oscillators may be replaced by surface acoustic wave (SAW) devices and MEMs resonators. Processors and radios can be operated at low voltages and low impedances. If some devices need higher voltages at trickles of current (such as LCD electrodes) they can be powered with capacitive charge pumps. At microwave frequencies, resonators can be made from strip-lines.

A server-sat uses a small array of radios (many more than the six shown) to communicate with neighbors in the array, with other arrays, and with the ground. Server-sats measure radio propagation time to neighbors to accurately compute spacing and orientation, with additional location information provided by other arrays, ground stations, and GPS. Multiple bands will be used, with atmosphere-penetrating bands used for down-links, and atmosphere-opaque bands used for server-sat to server-sat communication. Server-sats do *not* have dishes, but act together as a phased array antenna. A server-sat array in a 4 hour orbit is 7 times closer than a geosynchronous com-sat, so there is a 50x advantage in beam power and ground spot area. Round trip ping time to mid-latitudes is 70 milliseconds, less than U.S. transcontinental ping time through optical fiber.

Light Pressure and Optical Thrusters

Server-sats maneuver by light pressure. Solar illumination is 1300 Watts per square meter at the Earth's distance from the sun. For absorbed light, the light pressure is the power divided by the speed of light, about 4E-6 N/m^2 or 4 micro Pascal. If the light is reflected, the pressure doubles to 8 micro Pascal. The pressure is tiny (sea level atmospheric pressure is 100 kilo Pascals) but it is continuous. Light pressure pushing on a small, low-mass server-sat can add significant velocity over hours, weeks, and years. The areal density of a 100 micron thick server-sat is 0.233kg/m^2 , and the albedo of a solar cell is around 0.15. The acceleration is approximately 20 $\mu m/sec^2$, or 7 cm/min^2, or 256 m/hr^2. That permits significant local maneuvering.

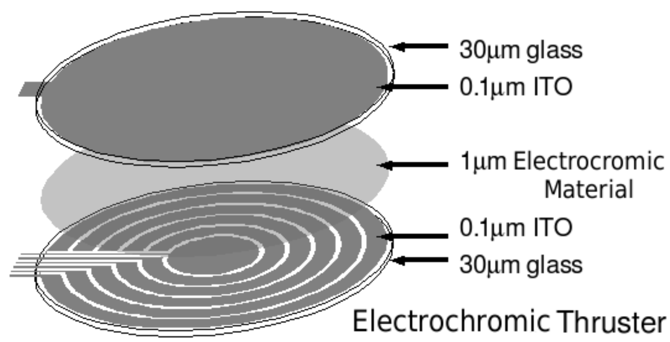
Large orbital changes are harder. Server-sats are in orbit, and light pressure accelerates them directly away from the Sun. That adds to orbital velocity as their orbit takes them away from the sun, but subtracts from orbital velocity as they approach it. If they are tilted in relation to the sun, less area is exposed to light pressure, and the "albedo vector" of reflected light tilts also, which adds a small sideways thrust.

Server-sats get the most power if they face directly into the sun. They tilt to maneuver. and that reduces the thrust. A 45 degrees sideways tilt produces 30% less power for computing and radio functions, which accommodate by slowing down. A 60 degree tilt produces half power (cooling significantly). The server-sat also absorbs infrared light from the earth, creating additional light pressure.

The version 2 design has three round optical-shutter light-pressure thrusters at 120 degree angles around the periphery. These are either reflecting or transparent. They are 5 cm in diameter, about 2 inches.   An ideal thruster produces 16 nano-Newtons when fully reflective, and zero thrust when transparent. Real materials show some reflection in transparent mode, and some transparency in reflective mode. Earth radiation (albedo and infrared) also reduces the effective thrust.

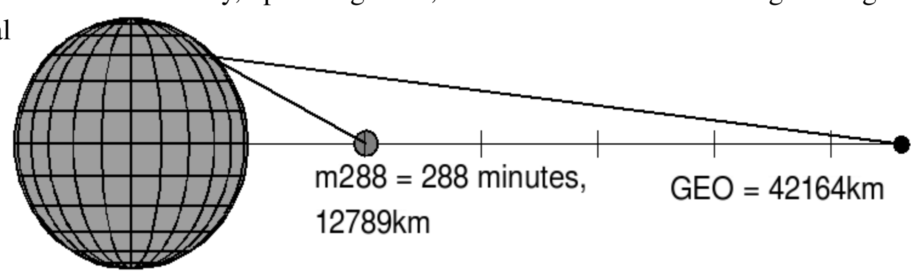
Achievable thrust may vary between 4nN and 12nN (WAG) per thruster. If a thruster on one side is reflective, while the other two are clear, the thrusters together produce a torque of 8nN times 10 cm or 800 pico-Newton-meters. If the entire server-sat has a mass of 7g and an average radius of 8 cm, the angular acceleration is 70 micro-radians per second squared. Accelerating for 36 seconds, then decelerating (applying opposite acceleration) for 36 seconds, turns the server-sat 10 degrees. Accelerating for 90 seconds, then decelerating for 90 seconds, turns the server-sat 60 degrees (not quite, as the thrusters are moving out of plane and become less effective when turned away from the sun). Roll control is indirect, by combinations of pitch and yaw [SSAT].

Optical thrusters are made from two thin (30 micron) layers of glass coated with of transparent Indium Tin Oxide (ITO) conductor on inner surfaces. The bottom layer glass is coated in separately controlled strips to permit partial functionality in spite of top to bottom shorts. In typical applications, a 1 micron gap is filled with electro-chromic shutter material and 1 micron diameter glass beads. A different spacing may be chosen if that improves performance or survivability.



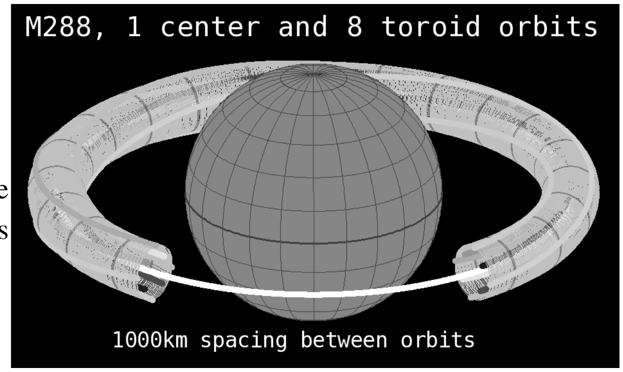
Correcting for tidal forces: At the four "45 degree" points in the orbit, tidal forces accelerate the server-sat. The near end is pulled inwards by slightly more gravity and slightly less centrifugal acceleration, and the far end is pushed outward by slightly more acceleration and less gravity.

For thin, low-mass server-sats, optical thrusters are more powerful than tidal forces, and easily keep the server flat towards the sun. The maximum angular acceleration of the server-sat is $\ddot{\theta}_{max} = (3/2)\omega^2$ or 0.29 µradians/s^2 for the m288 orbit, while the 5 cm thrusters can provide angular accelerations of 70 µradians/s^2 to a 7 g server-sat. The first experimental server-sats can be thick and heavy, up to a kg or so, but their altitude must be high enough so that light pressure exceeds residual atmospheric drag.



Deployment Orbits

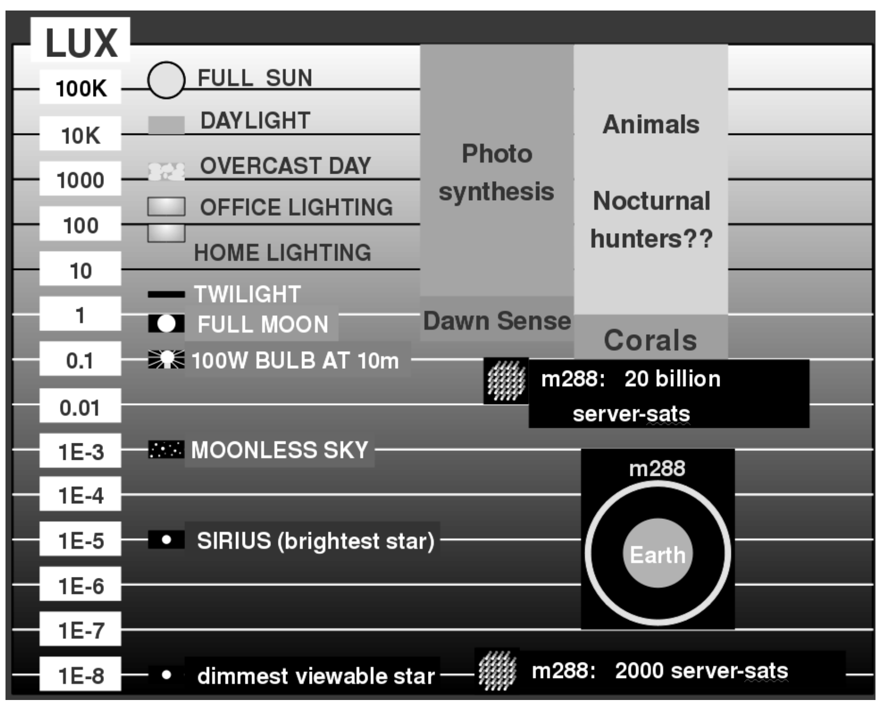
The first server-sat arrays will be deployed in a "4 hour" equatorial orbit, or more precisely a 14360.7 second sidereal orbit. This orbit passes over the same spot on earth 5 times per day (= 6-1, the earth turns underneath once per sidereal day), for a repeat time relative to the ground of 288 minutes (an **m288** orbit). A 4 hour equatorial circular orbit has a radius of 12789 kilometers, and an altitude above the equator of 6411 kilometers. This puts it in the “gap” of the Van Allen belt, with an estimated unshielded radiation dose of 1Mrad/year [citation needed].   Higher and lower orbit constellations are possible, but have higher radiation doses. Periods that are integer fractions of a day simplify launch and communication logistics.



Defining "property" within the m288 toroid: Many orbits can be mapped on toroids surrounding a central orbit. If they all have the same semi major axis as the m288 central orbit, they have the same 288 minute synoptic period. If the orbits are mapped correctly, every object in them maintains the same approximate spacing to neighbors in three dimensions, even as the whole constellation makes one orbit around the earth and one axial rotation around the central orbit. This allows very large numbers of server-sats to be deployed in the 600 million cubic kilometers of m288 server sky. Properties can be assigned much like ICANN assigns IPV6 address space. Indeed, we may map IPV6 addresses onto particular orbital volumes, and know where in the sky a particular server-sat is from its IPV6 address, or vice versa. 60 bits of address space maps to 1 meter cubes.

The m288 central orbit can be seen at 58 degrees north and south latitude, at a distance of 10500 km. The round trip ping time to 58N is 70 milliseconds. The ground ping time through optical fiber across the United States is faster in theory, but ground networks are slowed by switches, the slower speed of light in glass, and indirect routes. Some server sky packets may route "around the cloud". Without local caching in the "near" arrays, some pings may need 200 milliseconds to reach the far side of the orbit. This is still better than the 250+ millisecond ping time through a geosynchronous satellite, and up to 600+ milliseconds for multiple-satellite hops.

Night Side Temperature: When a server-sat orbits into the night side of the earth it shuts down. Thermal radiation from the earth's night sky heats it, and deep space cools it. At m288, the night temperature of the server-sat drops to 127K (-146C). Higher orbits have colder and longer "nights" and much longer "days".



Nighttime Illumination: Server-sats reflect some light. Oriented directly at the sun, most of the light reflects back towards the sun, but some will diffuse off angle. The sum of the diffuse reflected light from billions of server-sats may appear as cloudy light in a thin band around the equator, interrupted by the Earth's shadow.

Normally, the array will be under control, and night-side server-sats will be oriented to reflect incidental light away from the earth. Front surface treatments will reduce night-time illumination further. However, circumstances change, civilizations collapse, and the server sats may stay in orbit for millions of years, long after we lose the ability to control them. In the worst case, micro-meteor bombardment may damage surface treatments, and server-sats could tumble and scatter light in all directions.

Life evolved to adapt to existing cycles of day and night, full and new moon. Light pollution can alter this balance drastically, and perhaps destroy major ecosystems. The total number of server-sats in at m288 will be limited by **light pollution** and its effects on **corals** and **nocturnal animals**. Corals spawn synchronously to the monthly moonlight cycle, triggered by some fraction of full moon light. Confusing that process with light pollution could kill coral reefs, vast swaths of ocean life, and damage the oxygen generation processes that keep us alive. This may limit the **near-earth constellation** to less than **20 billion server-sats**. This problem needs more study, with oceanographers, botanists, and astronomers helping space engineers determine safe limits.

Deployment at the earth-moon L3, L4 and L5 Lagrange points reduces light pollution by 3600 times. These locations are 120 degrees apart, and follow the monthly lunar cycle. Three constellations of 5E12 server-sats will reflect 3E13 watts, and shine with 2% of the brightness of the full moon, in worst-case out-of-control conditions.

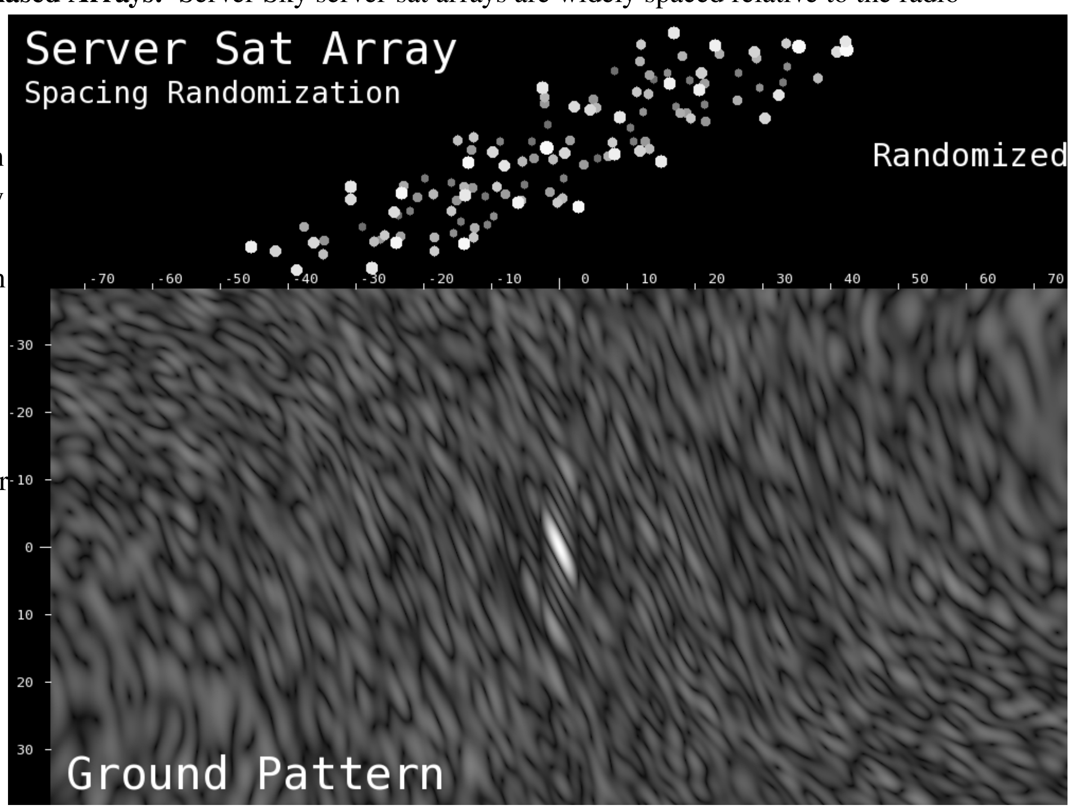
Radio Arrays

Server-sat radios will have multiple low-power outputs and connect to many printed-circuit antennas and resonant impedance matching structures. They will talk on multiple bands, for downlink, uplink, femtosecond-precision array timing, micron-precision server-sat location and orientation within the array, and orientation to other arrays and to GPS and ground systems. Accuracy derives from continuous monitoring and averaging, differential and quadrature analog signal processing, and the ultra-low vibration and perturbation of a completely predictable nano-gee space environment.

Down-link communications: As a new service, server sky may be allocated EHF frequencies [EHF] for the down-link. Assuming a frequency of 38GHz and a wavelength of 8mm, each individual server-sat antenna array can direct radio energy into an angle of about 6 degrees, for a 600km ground spot.

Server sats in **phased arrays** are more directional. Arrayed transmitters can beam the sum of many different phased signals to city-block-sized ground spots. The I and Q signal for each element is computed from the sum of many base-band signals representing different spatial channels. Digital vector processors combine many data channels and compute phased sums at high speed, recomputing transmit angles to accommodate the movement of the orbiting array relative to the ground (angles change 21 micro-degrees per millisecond).

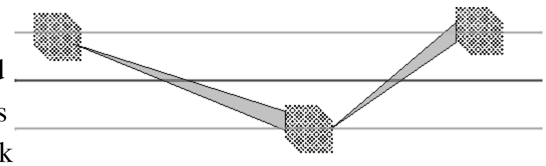
Three Dimensional Phased Arrays: Server Sky server-sat arrays are widely spaced relative to the radio wavelength. Array spacings are large compared to a radio wavelength, so they can scatter side-lobe energy into grating lobes. However, the spacing in the array can be continuously adjusted in 3 dimensions and 3 rotations, while avoiding radio and solar shading.



The brightest grating lobes can be smeared out and flattened by **randomizing** the spacing of the server-sats in the array, as shown in this **intensity plot.** This has the same effect as a sparsely populated array of much more closely spaced server-sats. A larger array suppresses the “clutter” noise by the square root of the number of server-sats. Precision maneuvering of the server-sats permits accurate random spacing, but a careful study of non periodic spacing functions will likely lead to a flatter spatial noise floor

Server sat arrays will communicate from satellite to satellite with individual high bandwidth 60 GHz beams. All the satellites within an array will need precision timing information, and each will get copies of receive and transmit packets for computing the phased array beams.

Communication between arrays will be difficult - not technically, but primarily due to licensing. The server-sky orbits will be approximately in-plane with equatorial communication satellites, which also use in-plane methods to communicate. This means that beams between server-sky arrays continue beyond the server-sky orbit and up to GEO, causing interference with receivers there.



This can be partially ameliorated by using very narrow, **oblique**, and fractional-orbit beams between server-sat arrays, such that the beams are pointed well above or below the orbital plane, and relatively weak when they reach GEO altitudes anyway. Space-to-space communications can use the 60GHz band, where the atmospheric absorption of oxygen is high. This isolates the space links from potential jamming on the ground.

The speed-of-light propagation time around the ring is 136ms. If packets are 1400 bits and running 10Gbps, the packet time is 140nsec. Assume that switching, re-route, queuing and beam forming time add a latency of 5 microseconds to each relay. 1000 hops adds only 5 milliseconds or 4% to the path latency, permitting an array spacing of 41 km. The increased path length of the diagonal adds more delay. If the oblique beams pass out of the ecliptic at a 19º angle (avoiding geosats), they add 6% to the total delay. As arrays get denser and larger, the beam size gets smaller, but inter-array traffic increases faster than the number of communication paths.

Ground communication via other satellite services: Server-sky operates near the equatorial plane. This restricts its usefulness for communications to ground sites at latitudes below 58 degrees, which precludes much of northern Europe. Existing services like Iridium, Globalstar, TDRSS, and the many satellites in GEO may be used as relays to extend the reach of the array, if permitted by the geometries and transponder configuration of these existing satellites.

Radar - locating space debris: The server sky array can help locate space debris and other satellites. Server sat antennas are too noisy and non-directional to make good radar receivers. However, they make dandy transmitters. Working in conjunction with existing radar satellites and ground stations, server sat arrays produce tight beams with high power density. Reflections off small bits of space debris can be detected by optimized radar receivers This permits accurate location and characterization of much smaller debris objects.

Orientation to other arrays, GPS, and ground stations: Server sky is blind. It does not have star trackers or ring laser gyros. It may have some MEMs gyros and accelerometers, but those are fragile and expensive to develop and the thinning needed may cost too much for Commercial Off The Shelf (COTS) devices. However, server sats can estimate the sun angle from solar cell output. Surface gratings can be added to sense sun direction. An isolated server-sat has some limited optical orientation capability.

A server-sat's main “sense” is radio. It shares timing information neighboring server-sats, permitting precision orientation and location computations. It can also measure signals from ground stations and GPS. Modulated radio and sub-wavelength fringes are used in commercial surveying equipment to measure distances with high precision. Server-sky does the same with the 60GHz intra-array communication links. If a server-sat measures phase within 1 degree at 60GHz, it can locate its many antennas with 20 micron accuracy. Continually upgraded software improves measurement capabilities.

Server Sat Mechanical Behavior

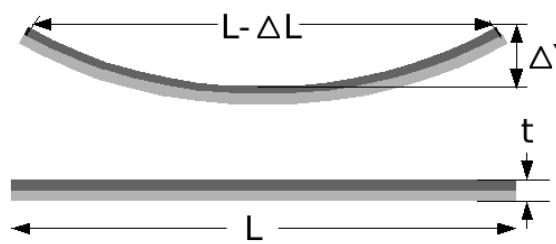
Silicon is the construction material of choice. The solar cell is silicon , as are the processors and memory. Since the server-sat undergoes wide temperature changes when it passes in and out of shadow, or undergoes thermal annealing, reliability improves if the non-silicon portions are made of composite materials that match silicon's 2.6E-6/K coefficient of thermal expansion (CTE).

Server sats need transparent materials and conductors that closely match silicon. The metals have very high CTEs, while SiO_2 has a very low CTE, so slotted metal wires with SiO_2 in the gaps can make a "material" that is both conductive and has the same CTE as silicon.

Stack compression during launch: Booster systems vibrate during launch. Regions of higher and lower compressibility and mass density may result in standing waves and resonances in a stack of server-sats. An ideal design matches the mechanical properties of all the materials used. The materials should have the same ratio of compressibility (modulus) to mass density, that is, the same speed of sound. This minimizes shear forces on the connections from the solar cells to the electronics and thruster ring. Stacks may also be resonance isolated from the boosters with springs and spacers, reducing the payload fraction. Mismatches restrict the number of server-sats that can be stacked between spacers.

Matching to **glass** rather than silicon may be better. Borosilicate glass has a speed of sound of 5.3km/s, silicon has a speed of sound of 8.0km/s, and pyrolytic carbon has the very low speed of sound of 1.5km/s. Thinning the silicon from 100 microns to 95.8 microns, and replacing the remaining 4.2 microns with pyrolytic carbon, results in the same 5.3km/s average speed of sound as glass. The "elastic impedance" is proportional to the energy stored by propagating sound. Sound waves reflect at impedance discontinuities. The impedance of borosilicate glass is 11.9 Kg/mm^2s. Composite silicon-pyro-C is 12.4 Kg/mm^2s. The composite also has 50% better thermal conductivity than silicon, because pyro-C is an excellent thermal conductor.

Curling occurs if the front and back sides of a server-sat (especially the solar cell) have different CTEs. The server-sat undergoes repeated thermal cyclings. There is nothing inherent in a server-sat that establishes "flat" - it flexes until tensions and compressions are minimized.



A slightly curved server-sat is not a severe operational problem. Turning up the edges a few degrees has little effect on collected solar energy. However, substantial curling changes the spacing of the radios at opposite sides of the curl, lifting them above the plane of the radios at the center of the curl.

Assume two materials with equal thickness and Young's moduli (the worst case for curl). Defining β as Δ CTE $\times \Delta T$, then the curl is approximately $\Delta L \approx (1/6) \times (\beta/t)^2 \times L^3$ and $\Delta Y \approx (1/4) \times (\beta/t) \times L^2$. A 150 millimeter solar cell, 100 microns thick, with ΔCTE =1E-6 and ΔT=100K, will have ΔL=0.56mm and ΔY=5.6mm. Server-sats should be designed for better CTE matching by balancing layer stack on both sides of the silicon, optimizing β towards zero. Work hardening should also be matched; materials that stretch and un-stretch repeatedly will deform over time, and this can also curl a server-sat.

Radiation

The M288 orbit (4 hour sidereal, 5 orbits per day relative to the earth) is located between the inner and outer van Allen belts. This is a high radiation environment compared to low earth orbit. Ionizing radiation damages semiconductors and data: Latchup, Single Event Upsets (SEU, bit flipping), oxide charging , and flash memory errors. Traditional satellites are damaged by this much radiation, and there are few satellites operating in these orbits. Server sky resists these effects.

The space radiation environment is well characterized with computer models such as AF-GEOSPACE [AFGE]. Radiation effects are tested empirically in ground laboratories, at high dose rates, and extrapolated to years of space radiation exposure. Ionizing radiation does nasty things to semiconductors, including latchup, gate oxide charging, and Single Event Upsets (SEU, bit flipping).

Latchup: SCR paths do not activate if the supply voltage is less than a diode turn-on voltage (typically more than 0.7V). The electronics in a Server-Sat are powered by a single-junction solar cell, which is a large forward-biased silicon diode. It cannot produce more than about 0.6V. Server-sats do not latch up!

Gate Oxide Charging: Silicon dioxide develops a positive charge when irradiated. An ionizing particle passes through, and generates hole-electron pairs. The electrons are highly mobile, and diffuse or drift out, while the holes get trapped, and leave a positive charge. Hafnium oxide develops a negative charge, trapping electrons. Recent work by Dixit [DIXI] shows that a combination of both materials produces a rad-hard gate oxide stack, withstanding 10Mrad from a Cobalt 60 source with minimal shifts.

Single Event Upsets: The charge deposited by an ionizing particle can temporarily overwhelm a logic gate, or change the state of a register bit. This causes incorrect computations. Sometimes, the cost is small. A calculation error in the I and Q signal of a software defined radio creates a little noise. CPU state errors are more costly. RAZOR error correction technology [RAZ] is being developed by the University of Michigan, MIT, and Intel. Digital integrated circuits are typically designed for high "noise margin", with extra power and voltage swing added, and clock rates reduced, to reduce the chances of a logic failure to infinitesimal probabilities. RAZOR reduces the noise margin, greatly improving the performance, at the cost of frequent errors. RAZOR adds error detection circuitry, and repeats calculations when errors occur. The performance improvement exceeds the cost of extra calculations, doubling overall performance. RAZOR technology will be common in microprocessors in a few years. Radiation-initiated single event upsets may be detected and corrected by RAZOR-like technology.

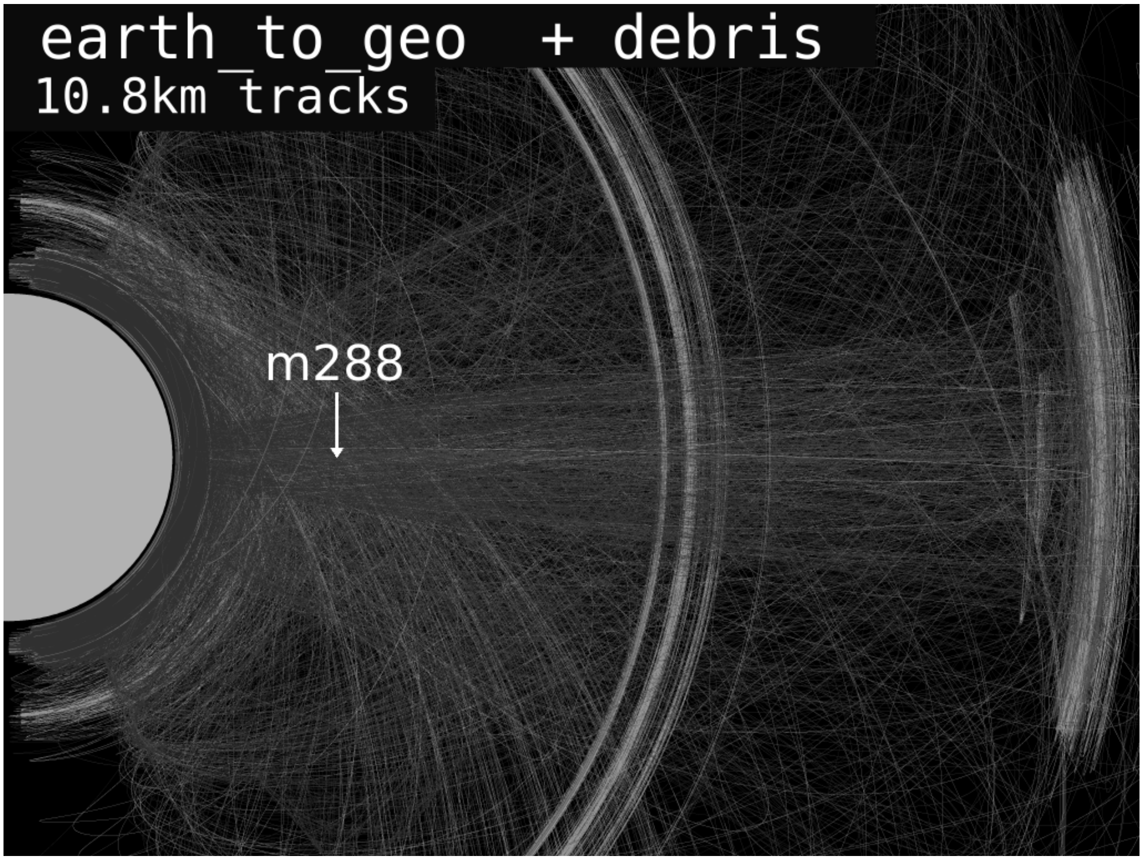
Space Junk and Debris

Collisions are a problem, especially for arrays like server sky which put huge numbers of assets into carefully defined and controlled orbits. Server Sky cannot be permitted to come close to such expensive assets as the Iridium communication satellites. The consequences of a collision are too costly.

Server-sats are cheap, and destroying one in a collision is unfortunate but not expensive. The main cost of a server-sat collision is more space junk, which can damage other server-sats. More robust objects (like traditional big-iron satellites) encountering server-sat fragments may lose a solar cell or two on the skin, but won't be destroyed. Still, it is bad manners to add to the debris problem.

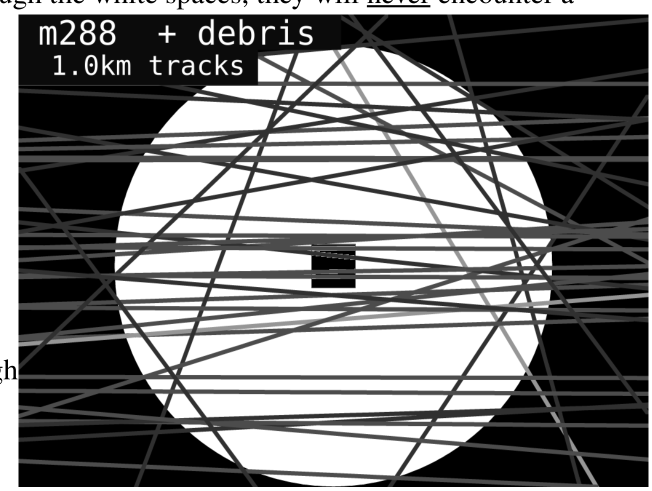
Server-sats can be maneuvered out of the way of accurately predicted collisions. Light pressure provides an unlimited supply of low thrust - in few hours, they can change orbit more than a kilometer away from a tracked impactor. Server sky will be deployed in orbits higher than most space junk. The vast majority of space debris is in lower orbits - it requires high launch velocities to even reach those altitudes.

This plot shows objects tracked by NORAD in orbits up to geosynchronous altitude. This is an "HV" plot. The horizontal H component represents the radius in the equatorial plane, and the vertical V component represents the distance north or south of the plane, of the locus of each orbital track.



The distances represented by the plot are vast - 44000 kilometers wide, 33000 kilometers high, more than 10 times the land surface of the earth. The volume of space represented is enormous, 200 trillion cubic kilometers, or 400 thousand times the volume of atmosphere in which we fly all the world's airplanes. Except for the bands of navigation and communication satellites above LEO, the density of tracked objects drops off exponentially with altitude. The collision problem decreases greatly at altitudes above 1000km.

This plot shows just the m288 region. The square in the center of the plot is 10 kilometers on a side, as big as the city of San Francisco. If Server Sky orbits are threaded through the white spaces, they will never encounter a NORAD-tracked space object.



NORAD does not track everything, especially small sub-centimeter objects difficult detect with ground-based radar. Orbiting radars can do better using very short wavelengths and large aperture antennas. Until that detailed mapping is available, unavoidable collisions will occur. Centimeter objects that merely destroy a solar cell or two on a large satellite may shatter a server-sat. Perhaps server-sats can be designed to survive a sub-centimeter collider passing through them. If a collider only hits one segment of the solar cell, the server-sat can keep functioning at lower power.

Possibilities

Long term speculation follows. We can bypass many limits to growth by moving more computation, communications, power production, and manufacturing into space and away from the biosphere.

Tera scale Arrays and Beam Power: Big compute jobs like weather prediction or animation rendering are not real-time. Larger latency is tolerable. Server-sats in the Earth-Moon Lagrange positions are 60 times further away from earth than m288, so they produce 1/3600 of the worst case night-time illumination. Trillions of server-sats may be deployed in the Lagrange positions, with round trip ping times of 2.5 seconds. Later generations of server-sats may become "compute-light" and "transmit-heavy", beaming the power as microwaves to rectenna arrays on the ground, making power for the electrical grid.

Lunar Materials: Most of the mass of a server-sat is silicon, glass, and aluminum, which are the principal constituents of lunar rock. Integrated circuits will be made on earth for a long time, but lunar-manufactured solar cells are a possibility. A cubic meter of lunar regolith could be used to manufacture perhaps half a million 3 gram solar cells, which could be mated to earth-manufactured integrated circuits in an automated facility in orbit. Orbiting those server-sats with an electromagnetic launcher requires about 18 billion joules, energy they can produce in 10 hours. Astoundingly rapid investment payback is possible with lunar materials.

Deep Space Arrays: Server-sats orbiting between Earth (1.5E11 meters from the sun) and Mars (2.3E11 meters) could capture much of the light of the sun. Server-sats at 1.9E11 meters distance from the sun, receiving 800 watts per square meter, have an equilibrium temperature of 270K. If they cover 2% of the sky, they raise the average deep sky temperature from 2.7K to 100K, which raises the Earth's equilibrium temperature by 1C. These septillions of server-sats can generate 1E24 watts of usable electric power for computation and space manufacturing, millions of times the solar power received by the Earth.

Low cost launch: The launch loop [LOOP] is an electrically powered earth-to-high orbit launch system. The main construction and operating cost of a launch loop is electricity. At 10 cents per kilowatt hour, and a quick payback of capital, a launch loop can put a kilogram into orbit for about $5, and a small launch loop can launch 80 tons into high orbit per hour.

A 7 gram, 2 watts-to-ground-collector server sat can be orbited for 12 cents. Collected by a rectenna for 5 cents per watt, with a lifetime of 20,000 hours, a one dollar investment produces 100 kilowatt hours. This cheap electricity drops the cost of further launches. Thinning the server sats down to 1 gram saves more.

Conclusions

Server-sky is speculation. There are many unsolved problems, and more will appear during implementation. Fortunately, the problems encountered so far have shown signs of solution. With enough imaginative contributors, other problems and solutions will emerge, often from unlikely places elsewhere in the world.

Server-sky may be the near-term commercial application that pays for the permanent expansion of life and civilization into space. It may also save the biosphere from destruction, by removing large scale computing and power generation from it.

Server sky is open technology. The idea will affect the entire world, and the world must be engaged in doing it right. Working together, we will succeed.

References

[AFGE] **http://www.kirtland.af.mil/library/factsheets/factsheet.asp?id=7899** AF-GEOSPACE is a collection of programs that model the radiation environment near earth

[ALIX] **http://wiki.keithl.com/index.cgi?SL5Alix** The 4 watt ALIX board from PC Engines, using an AMD Geode X86 processor, producing 900 bogo-MIPS performance.

[AREA] **http://www.osti.gov/bridge/product.biblio.jsp?osti_id=764362** An estimate of road and roof area in the region around Sacramento; multiply by the population ratio of 230 for the US. WAG.

[ATOM] **http://www.intel.com/products/processor/atom/** Intel Atom low power processor.

[BEKE] **http://www.thespacereview.com/article/131/1** Advanced Space System Concepts and Technologies: 2010-2030+, Ivan Bekey, 2004.

[DATA] **http://www.energystar.gov/index.cfm?c=prod_development.server_efficiency_study** E.P.A. estimate of data center power usage.

[DEBR] **http://apollo.cnuce.cnr.it/rossi/publications/iau/node2.html** A 1994 estimate of space debris. There is more now, but it follows the same pattern.

[DIXI] **http://www.isde.vanderbilt.edu/content/muri_2008/dixit_muri2008.pdf** Sriram Dixit et. al. at Vanderbilt University. Recent work on HfO/SiO2 stacked gates and radiation resistance.

[EHFR] **http://en.wikipedia.org/wiki/Extremely_high_frequency** 30 to 300GHz. Short wavelengths permit better focusing, and are above most communication bands, facilitating license assignment.

[HOTB] **http://en.wikipedia.org/wiki/Hot_Bird_9** Hot Bird 9, a modern TV direct broadcast communication satellite.

[LOOP] **http://launchloop.com** The Launch Loop wiki website.

[RAZO] **http://deepblue.lib.umich.edu/handle/2027.42/62283** Razor II variability tolerant computing design.

[SMAD] **http://www.smad.com/about/smad3.html** Space Mission Analysis and Design, Wentz et. al., 3rd edition.

[SMAL] **http://www.researchchannel.org/prog/displayevent.aspx?rID=3427&fID=345** An excellent lecture video about the Terawatt Challenge by scientist Richard Smalley.

[SSKY] **http://server-sky.com/RollControlV01** Roll from pitch and yaw

[SSPS] **http://gltrs.grc.nasa.gov/cgi-bin/GLTRS/browse.pl?2004/TM-2004-212743.html** Space solar power satellites

[TOOLS] **http://server-sky.com/tools** The open source tools used to create the website and this document.

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