Server Sky - Computation and Power in Orbit

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***Abstract*—Arrays of small ultrathin satellites may someday outperform aircraft-sized satellites. Terrestrial data centers and fiber optic networks are unaffordable in developing countries, but data services delivered from orbit through existing cell towers can serve rural communities and provide jobs in the global economy. New solid state technologies permit mass-produced, paper-thin, 20 cm wide five gram "thinsats", producing 4 watts with 75% availability. Phased arrays of 8000 thinsats in 6400 km altitude orbits can maneuver with light pressure, and communicate simultaneously with hundreds of kilometer-wide ground footprints. Arrays of small solar-powered satellites can outperform aircraft-sized satellites. Space solar power allows exponential power growth without destroying natural habitat.**

***Index Terms*—Space Technology; Integrated Circuits; Solar Energy; Internet; Globalization**

I. Introduction

Data centers consume almost 3% of US electrical power [1], a fraction doubling every 5 years, growing faster than efficiency improvements. Terrestrial solar power production requires transmission lines, mechanical structure, and land/habitat diversion, suffering from dis-economies of scale. Systems diverting land and energy from nature cannot be truly sustainable.

Developing rural regions in India, China, and Africa cannot afford capital-intensive, logistically sophisticated data centers and vast fiber optic networks requiring 24×7 electrical power and high-tech maintenance skills. With high bandwidth connections to the global internet, the people in these areas can offer the most valuable commodity on the internet - trained, diligent attention - and rapidly improve their education and economic condition.

How can this happen without expensive rural infrastructure?

II. Space Based Solar Power

> "Space Solar Power is a great dream, achievement of which is a great necessity for the 21st century world." — Dr. A.P.J. Abdul Kalam [2]

Dr. Kalam, chief scientist of India's rocket development program and President of India from 2002 to 2007, proposes space solar power for India's future energy supply.

The sun produces 384 trillion terawatts that nature cannot use, streaming past the planets into interstellar space. Space is expensive to get to, but zero-gee structures can be incredibly thin and ultra-light-weight, permitting solar photovoltaic systems that are cheaper to deploy in orbit than on the ground. A 5 hour orbit offers 20 hours a day of unattenuated, cloud-free 1360 W/m^2 sunlight in a stable, clean, zero-maintenance environment. Sunlight captured in space does not steal land and sunlight from agriculture and wilderness on the ground.

Some space enthusiasts imagine huge structures in geosynchronous orbit capturing gigawatts of solar power and beaming it as microwaves to receivers on earth, 40 000 km away [3]. Because of beamforming diffraction limits, both transmitting and receiving antennas must be enormous.

When American farmers settled west of the Allegheny mountains, 600 kg of rye required three pack animals to transport to eastern markets, and sold for $6. The same rye could be distilled into 30 liters of whiskey, transported on one pack animal, and earned profits approaching $16 [4].

Space power faces similar transportation difficulties, and similar solutions. Transforming space power into high value products before shipment reduces costs and increases value.

Data center computation is very expensive and energy hungry. Google consumes 300 MW [5]; estimating $80/MWhr wholesale rates worldwide, they pay more than $200 M/year for electricity, which Google transformed into information and advertising revenues of $33 B in 2011 [6], with some adwords earning more than $50 per clickthrough.

Systems that convert space solar power into computation and transmit the results to earth, bypassing energy and capital intensive fiber networks, may prove cheaper to operate and to deploy, especially in regions without established high-bandwidth infrastructure.

III. Cell Phones in Afghanistan and India

The developed world has massive networks of freeways, waterways, airways, pipelines, wires, and optical fiber, connecting resource extracting regions to resource consuming regions over small and large distances. Sometimes this makes surprising ecological sense; for example, moving food by ship from regions with different harvest times can use less land and energy than storing suboptimally grown food for months.

We can accomplish more with less by moving information rather than mass. Information is infinitely replicable at low cost, so moving agricultural information, economic information, and new ideas and techniques requires far less infrastructure than moving gigatons of mass.

Glimmers of information abundance are appearing in the developing world. In Afghanistan, Roshan [7] deploys low cost, feature-rich cell phones with eBanking, weather, and crop market reports, using interactive voice response systems, essential in a country with 28% literacy. Afghan police are paid through their phones, rather than with banknotes, increasing take-home pay while reducing corruption and absenteeism.

These cutting-edge communication deployments are models for new 21st century technologies. China and India each have more than 100 regional languages. A cell phone system with additional computing resources can provide basic speech translation. Automated education, medical services, and global commerce can enrich the lives of the poorest citizens, without increasing material and energy consumption.

Server sky ground antennas added to cell towers can reduce the cost of new deployment and increase the value of existing towers. New services may also include local weather prediction and warnings, emergency services, eGovernment, eLogistics, and new job opportunities in a global market.

Sensor equipped "medical phones" and "agriculture phones" for telemedicine, soil measurement, pest, microbe, and hazardous waste identification will allow hospitals and agricultural institutes anywhere to gather data and provide instant advice to local paraprofessionals.

India is modernizing rapidly [8]. India has 400 000 cell towers, mostly off the electrical grid, consuming three billion liters of diesel per year. India plans to deploy solar PV and batteries to produce up to 5 kW per base station [9]. With 340 million rural cell subscribers, and a monthly growth rate of 2% [10], India is connecting its rural population, while increasing adult literacy from 64% in 2001 to 74% in 2011 [11].

The Indian Space Research Organisation (ISRO) is among many Indian organizations developing world-class technologies. India can produce and launch server sky with indigenous resources, supplemented with advanced semiconductor processing from advanced companies like Intel.

IV. Current Satellite Technology

Traditionally designed space satellites are expensive, both to build and to launch, but work with relatively cheap ground antennas. Satellite costs are shared by millions of users.

Satellites are currently built with aircraft technology: costly, slow to build and deploy, assembled and tested manually a few at a time. The electronic components are years to decades behind low cost consumer electronics. This is as it must be; when failure is not an option, neither is rapid evolution.

Direct broadcast satellites in geostationary orbit send high power microwave beams to large regions with millions of small terrestrial receiver dishes on stationary mounts. Diffraction effects make ground spots large, with diameters proportional to the transmit distance times the wavelength divided by the antenna diameter. A two meter Ku band (2 cm) antenna 40 000 km from the earth makes 1000 km ground spots.

Antennas in lower orbits using shorter wavelengths make smaller spot sizes, but the satellites are not geostationary and move rapidly across the sky, inaccessible for most of their orbit. Many satellites are needed for complete coverage, 66 for the Iridium satellite telephone constellation. Iridium satellites orbit at 780 km altitude, with 1.6 GHz (19 cm) ground links. When the satellite is directly overhead, the ground spot size is 100 km and the satellite moves 30 degrees per minute across the sky. Inverse square law, and satellite motion, means that handheld devices must transmit high power isotropically to reach distant and fast moving satellites. In regions where optical fiber, cell towers and cell phones are already deployed, specialized satellite phones are expensive and unnecessary.

The 6740 kg ViaSat-1 satellite, launched on October 19, 2011, provides 72 Ka band (26 to 40 GHz) spot beams with >140 Gbit/s total capacity for $500 M satellite cost. ViaSat-2, slated for launch in 2016, is expected to cost $625 M and serve 150% more customers [12]. An impressive improvement, but in the same time semiconductors will grow 2.5 times faster.

Both satellites are geosynchronous "bent pipe" systems that relay information from the terrestrial internet to dish-using remote customers, requiring two back-and-forth 250 ms trips, plus terrestrial internet latency and queueing delays, for every internet transaction. Costs exceed $700 per new subscriber, with $50/month buying 12 GB of data transfer.

The up-front costs for satellite technologies put them beyond the reach of most developing nations. This paper proposes a cheaper way to deliver far more satellite capability, and grow much faster.

V. A Solid State Makeover

Ivan Bekey teaches us to replace structures with information, build gossamer structures in distributed systems, and transport energy and information, not mass [13]. Middle Earth Orbit (>2000 km altitude) is subject to extremes of radiation and temperature, but is free of friction, contamination, and mechanical stress. Satellites have line-of-sight access to vast areas of the earth. Orbits are precisely predictable.

Mesh networks can connect thousands of small satellites in a three-dimensional obstruction-free environment. Whole-system function-to-weight ratios can be orders of magnitude better than terrestrial solar and aircraft-style satellites.

A satellite is a surface that collects solar power, which drives sensors and computation and transmitters to receivers on the ground. This surface can be very thin and lightweight.

220 nm thick direct-bandgap indium phosphide photovoltaic cells can collect sunlight at about 15% efficiency, 200 W/m^2 [14]. Without wiring, the InP alone weighs 1 g/m^2 .

A powerful computer with solid state memory can be built with 10 cm^2 of unpackaged silicon. If the die are 750 μm thick, that is two grams of silicon. Thinning die to 50 μm reduces mass to 130 milligrams. The chips for a powerful computer and the solar cells to power them can cost less than $20 to launch into orbit, even at launch costs of $10 000/kg.

If we design space systems to minimize packaging and wiring weight, and assemble them with photolithograpy and automation, launching chips and photovoltaic power supplies into space can cost less than packaging and deploying them on earth, with more versatility and fewer environmental costs.

VI. Thinsats

Server Sky converts space solar power into computation in distributed arrays of small solid-state satellites. Server sky

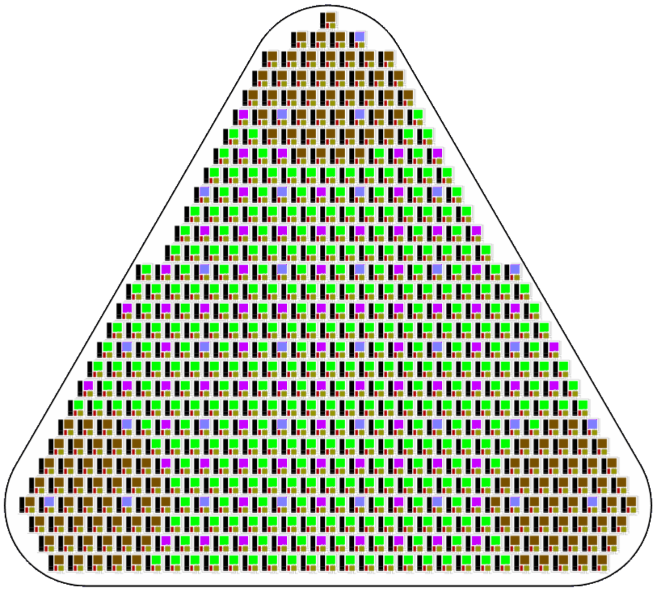

Fig. 1. Thinsat back side chip array, 20 cm wide, 80 μm thick, 5 grams. The black vertical bars represent slot antennas, the corners are electrocromic light pressure thrusters. Antenna slots pass through the aluminum foil substrate to the front, which has light pressure thrusters in the corners, and InP photovoltaic cells in between.

thinsats are rounded triangles 20 cm across, 240 cm^2 in area, and weigh five grams. Thinsat front sides are covered with indium phosphide solar cells. Thinsat back sides, illustrated in Fig. 1, are covered with a grid of wiring and arrays of small integrated circuits, including processors, flash memory, and radios. The radios feed slot antennas cut through the 80 μm thick aluminum substrate, arranged in a hexagonal grid at half-wave spacing. Thinsats cool by black body radiation, and maneuver with light pressure, with switchable electrochromic mirrors adjusting the small but continuous light pressure force.

Distributed function makes thinsats highly redundant and tolerant of micrometeoroid punctures. The chips are directly powered by solar cells millimeters away, reducing voltage drop and wiring weight.

VII. Server Sky

Server sky thinsats are deployed into actively stabilized three dimensional geodesic arrays. The size of the array can be adjusted from hundreds to millions by moving thinsats between arrays. We will consider arrays of 8000 thinsats, producing as much as 32 kW and an average of 24 kW of power for computation and radio.

Server sky orbits are not geostationary. Thinsats are launched in 40 kg solid-cylinder stacks into 6411 km altitude equatorial orbits, about twice the radius of the earth. This is in the inner van Allen belt, a high radiation zone with few other active satellites. The lower altitude reduces round trip ping time, path-length attenuation, and the size of the ground footprint for point-to-point communications.

Equatorial orbits have many advantages. They have minimum collision velocities with other satellites, zero collision velocity with other arrays, they are not in the wrong hemisphere half the time, and they stay in the same layer of the van Allen belt. Server sky arrays are *not* comsats, but sources of data service, so their individual availability should be predictable.

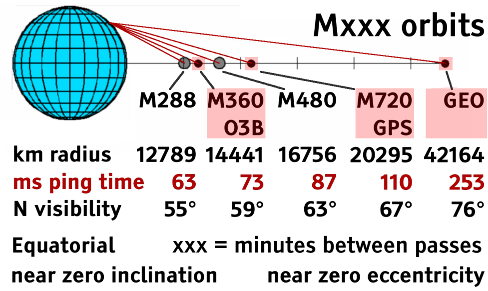

Fig. 2. Server sky M288 equatorial orbit radius and one-trip ping time. Repeater comsats without onboard data centers will need trips up and down between user and terrestrial data center.

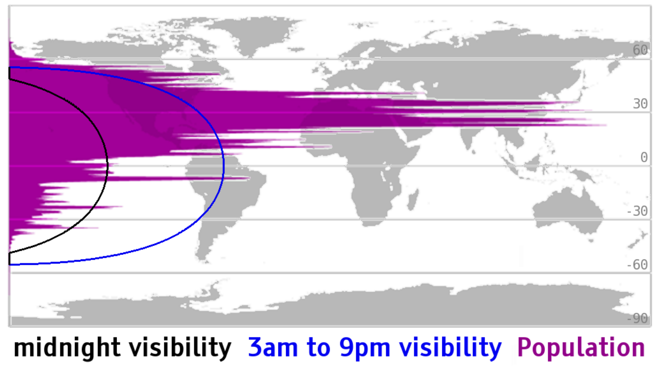

Fig. 3. Graph of population and array visibility. The vertical axis is latitude south to north, and the horizontal axis represents M288 array midnight and daytime visibility vs latitude, and world population vs latitude. Array visibility is lower at midnight because arrays are eclipsed by the earth.

Arrays pass through the sky five times a day, every 288 minutes, so this orbit is called **M288**, as shown in Fig. 2. In the northern hemisphere, the M288 orbit appears close to the southern horizon, and is not visible from the poles to the 60th latitude north or south. Arrays are visible for more than one hour per daytime pass between 40° latitude north or south, assuming 5 degrees elevation above the horizon. Data and programs are replicated across many arrays, for redundancy and global 24 hour availability.

Thinsats spend part of their orbit in eclipse as their circular orbits take them behind the earth, into the night sky. This reduces night night time array visibility, more at higher latitudes. The time spent in eclipse is 16.6% in spring and fall, and as low as 10% in summer and winter, due to the axial tilt of the equatorial orbit.

The M288 orbit is not visible above 60°N. Fig. 3 shows most of the world's population below that northern latitude [15]. Farther north (and south), and near midnight, server sky arrays can relay through existing constellations such as Iridium and Globalstar to polar and insomniac customers.

A medium-sized booster such as ISRO's PSLV [16] can put

24 arrays into equatorial orbit, with 6 arrays visible at once at 40°N latitude at noon, and 2 arrays at midnight.

VIII. Light Pressure Maneuvering

Thinsats have an area to mass ratio of 5 m^2/kg, and maneuver like light sails, such as the Japanese Space Agency's IKAROS [17]. Thinsats have far less sail area per mass than true solar sails, but can adjust their position in arrays, maneuver out of the paths of colliders, and migrate from underutilized arrays to larger ones.

1360 W/m^2 sunlight makes a tiny 4.54 microPascal pressure if it is absorbed, and double that if reflected. Most of the thinsat is low albedo for maximum light absorption and infrared thermal emissivity.

The three corners of a triangular thinsat (on both front and back) are 5 cm diameter (19.6 cm^2 switchable electrochromic mirrors, which switch from dark to reflective. The switch changes the solar sail thrust by 18 nanonewtons and acceleration by 3.5 μm/s^2. Thinsats normally operate at half thrust. A thinsat can change relative to array center by ± 1.8 μm/s^2. The electrochromic mirrors are segmented into 200 9 mm^2panes, so acceleration is adjustable down to ± 16 nm/s^2. If the electrochromics switch with 10 second precision, position can be adjusted to 0.4 μm accuracy, calibrated by radio time of flight to neighboring thinsats.

Electrochromic materials change color by adding or subtracting a mobile ion, typically hydrogen or lithium, in an electrochemical cell. Electochromism is commonly used for electronically controllable automobile mirrors [18]. $Ni(OH)_2$ (nickel hydroxide) changes from transparent to brown NiOOH if a hydrogen ion is removed; WO_3 (tungsten oxide) changes from transparent to blue $H+WO_3$ if a hydrogen ion is added. Two thin layers of these materials, separated by a porous solid electrolyte layer, form the electrochromic cell. The cell switches from transparent to dark by putting a positive voltage on the nickel layer and a negative voltage on the tungsten layer. Reversing the voltage switches the cell back to clear. The cell is backed by an aluminum mirror on the tungsten side, and a transparent front electrode like Indium Tin Oxide (ITO) or Aluminum Zinc Oxide (AZO) on the nickel side. If the front electrode is positive, the cell turns dark, if the electrode is negative, the cell turns reflective.

Thinsats turn when the corners are adjusted to different thrusts. We can approximate the reflecting corners as accelerating outbound relative to the thinsat center 10 cm away, so the radial acceleration is 350 μradians/s^2. Thinsats turn and stop at a 45 degree angle in 16 minutes.

The reflection from the mirrors from a tilted thinsat is off axis to sunlight. The perpendicular component of the reflection creates a small sideways acceleration.

Accelerations are small, but can accumulate to significant velocity changes and displacements, allowing thinsats to maneuver relative to the rest of the array. If a thinsat accelerates for 30 minutes and then decelerates, it moves 5.7 meters relative to the rest of the thinsats. The array and orbit turns, so only half the orbital period is available for in-plane accelerations in a particular direction. For long maneuvers, divide the peak acceleration in half, so a 12 hour acceleration followed by a 12 hour deceleration results in a 1.6 kilometer movement. The displacement is square law versus time, so a 10 day maneuver results in 160 kilometers of movement, 20 days 640 kilometers, and so forth. A thinsat can move 40 000 kilometers, halfway around the M288 orbit, in 160 days.

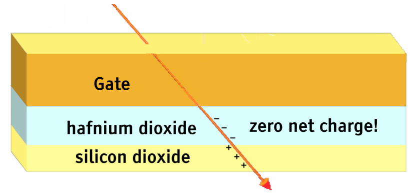

Fig. 4. Charge compensation in HfO_2 / SiO_2 gate stack

Migration means arrays can grow or shrink, merge or split, as opportunities appear. Fixed transponder satellites and terrestrial data services are not nearly as fluid and adaptive.

If a collider punches through a thinsat, it may deposit some momentum and put the thinsat into a tumble. The thrusters on front and back can adjust the torque to slowly reduce the tumble, though months of small acceleration may be required to remove a fast tumble. Roll can be removed by nutation, as if rolling the thinsat around an imaginary cone. A tumbling thinsat cannot contribute productively to the array, and light pressure changes will push it out of the formation. When the thinsat recovers, it can return to the array and resume function, or move to a collection point for recycling.

IX. Radiation

Radiation is the number one problem for server sky thinsats. We will not know whether thinsats will work as intended until we test them with radiation on the ground. Fortunately, we can test and harden at the individual component level, and our discoveries will help semiconductor manufacturing in general. Recent advances in solar cell materials and VLSI radiation hardness, mostly an accidental result of device shrinking, offer promising techniques to build unshielded gram-scale satellites.

The Intel hafnium dioxide gate stack, designed to reduce gate leakage, accidentally produces FET gates highly resistant to charging by ionizing radiation. Fig. 4 shows an ionizing particle penetrating the gate. As it smashes through the gate insulators, it creates hole-electron pairs. The electrons are mobile in hafnium dioxide, leaving behind holes. In silicon dioxide, the holes are mobile, leaving behind electrons. With the right proportion of oxide thicknesses, the charges compensate each other and gate threshold voltage shifts fall to less than a millivolt per megarad [19, Fig 7.3].

Modern digital processes operate at supply voltages too low to sustain latchup. Lower voltages lead to reduced noise margins and susceptibility to thermal noise causing bit flips. Recent research to build microprocessors that recover from random thermal errors [20] can evolve into systems that recover from radiation-induced single event upsets. In many cases, calculation errors result in acceptable acoustic or radio phase noise. We need only provide error correction for calculations that cannot tolerate errors.

Thin indium phosphide solar cells have high radiation resistance. Thin cells capture less light than thick cells, but use far less expensive indium. 220 nm cells built with graded junctions and drift fields rapidly sweep minority carriers towards the junction for collection, greatly reducing sensitivity to traps caused by radiation damage. Thin cells survive radiation doses of 10^{18} electrons/cm^2(1 MeV) [14]. InP has low surface recombination velocity, so polycrystalline InP can be used, further reducing production and material costs [21].

Thinsats cool by black body radiation, and have low lateral thermal conductivity. We can divert all of a thinsat's power into a few chips and heat them to high temperatures to anneal lattice damage. With occasional annealing [22], advanced electronics may survive for years, unshielded.

The research is promising but not conclusive. A small lab can replicate the studies, and optimize strategies for thinsat production. Fifteen year, 100% survivability is unnecessary. Thinsats are highly redundant, and can produce results in spite of significant damage. The biggest risk is obsolescence; in 10 years, an new thinsat may offer 30 times the performance of an old one, and old thinsats will be recycled as ballast mass.

X. Geodesic Arrays, Radio, and Ground Patterns

The grid of slot antennas on a server sky thinsat forms a phased array antenna. The entire array of thinsats combines into a larger antenna, which can simultaneously send hundreds of narrow packet beams to kilometer-sized receiver footprints.

The zero gee environment, orbital mechanics, and the avoidance of shading of one thinsat by another, leads to different array designs than the planar grids of rigid phased array antennas.

One promising strategy places thinsats in a distorted geodesic sphere. Icosahedral geodesic spheres consist of 20 triangular panels of tessellated points. For V points per icosahedron edge, an array will contain $10V^2+2$ thinsats. A V=28 array, shown in Fig. 5, contains 7842 thinsats. Thinsat spacings of 1 meter make a V=28 array 100 meters across. A small V=4 array of spares may orbit nearby.

The arrays are distorted by orbital mechanics. A radial distance increase of 1 meter turns into a trailing distance of 2 meters a quarter orbit later, and the arrays rotate around their central axis once per orbit. This is difficult to convey with a static picture, see the server sky website [23] for animations.

Thinsats are widely spaced in arrays, and do not form a continuous sheet of radio emitters. This means that most of their radio emissions are splattered uselessly into sidelobes. In typical two dimensional phased arrays, wide spacing leads to off-axis grating lobes, pathological regions of highly concentrated radio energy that create interference at sites distant from the intended target.

Geodesic arrays splatter just as much power into sidelobes, but have the surprising property that they do not create high intensity grating lobes. Power is still wasted, but it is smeared

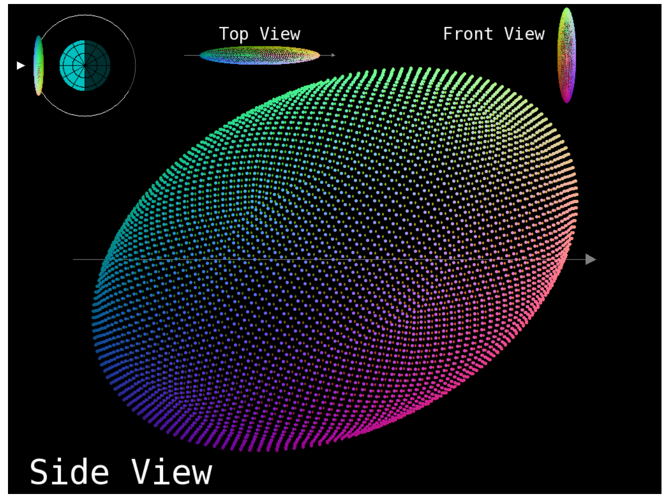

Fig. 5. 7842 Thinsats in a Geodesic Array

nearly uniformly over the ground, adding to background noise but not creating high gain interference. Server sky arrays are point-to-point, not broadcast, so every nanowatt that isn't collected by the intended antenna is wasted anyway. The wide arrays tend to make very small ground spots, and the distribution of thinsats, more densely populated around the edges, reduce the ground spot still further. Assuming a 70 GHz (4.3 mm) downlink, the ground spot is 300 meters across between the first Airy nulls. An array can simultaneously address two targets a kilometer apart with two different Gbps signals. This will not provide superhigh bandwidth to a dense urban environment, but it is more than adequate for suburban and rural customers.

Ground antennas will also be phased arrays, perhaps cheap rectangular panels of semipassive slot antennas designed to track arrays across the sky and address different arrays packet by packet. Imagine a 10 cm by 100 cm, 1 Gbps panel and LNA with 4% receive efficiency. 8 nW/m^2 is more than adequate illumination for a usable bit error rate with post-correction.

The ground pattern is a superposition of two Airy disks. The sidelobe pattern is 300 km radius (to the first Airy null) with a peak intensity of 1pW/m^2 and a total power of 77 mW. The target pattern is 400 m average radius, with a peak intensity of 8 nW/m^2 and a total power of 1.3 mW. 8000 thinsats with 1000 slot antennas each produces 80mW, so the transmit power per slot is 10nW. If the arrays address 100 ground targets simultaneously (by superposition), the total slot power is 1μW. Radar, discussed later, may transmit as much as 1mW per slot.

Both north-south and east-west antenna polarizations are available. Different countries have different policies regarding the information available to their citizens. We can arbitrarily assign east-west polarization to *managed* internet services, and north-south polarization to *open* services. Visual inspection of the ground antennas shows which services they receive. Unless varying national policies are accommodated, the International Telecommunications Union (a consensus body) may refuse to

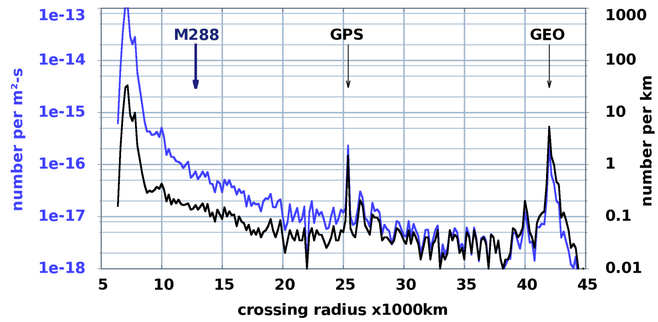

Fig. 6. Objects crossing through the equatorial plane, number per square meter per second (object flux), and number per kilometer altitude. The M288 orbit has 1000 times fewer potential colliders than low earth orbit.

assign orbit and spectrum.

XI. Collision Vulnerability

The general public thinks of collisions with space debris as the greatest hazard faced by satellites. The risks are serious, but they are subtle. Actual collisions are rare, once every few years, and usually between two of the derelicts comprising most of the objects in orbit. The actual risk is that the collisions create a cloud of more colliders, increasing the future collision rate. This exponential multiplication process is slow, with multiplying times in the decades, but each collision increases the cost and difficulty of disposing of a growing population of smaller objects. We haven't yet deployed systems to collect debris.

Most debris objects are in low earth orbit (LEO), as shown in Fig. 6. Server sky will be deployed far above LEO, where the collider density is 1000 times smaller. Hitting a thinsat will not produce a cloud of large, dense debris objects, nor is a thinsat likely to penetrate a larger satellite. The debris from an collision will be small, much less mass than the debris from macro- satellite collisions.

Because thinsats can maneuver continuously, arrays can move out of harm's way if a debris object is observed on a collision path. Ground based radar systems in fixed locations make these observations today, but infrequent surveys and limited visibility through a distorting atmosphere can't detect the smallest objects, nor predict collider positions more precisely than 1 km. Reacting to every possible threat will quickly exhaust the thruster fuel on big satellites; thinsats never run out of thrust.

XII. Tracking Space Debris with Server Sky Radar

Internet customer demand will grow exponentially, but in the beginning demand and revenue won't pay for server sky. Thinsats are adaptive millimeter-wave energy sources, and can be repurposed for look-down radar.

Accurately predicting, days in advance, a collision that might destroy a billion dollar satellite or the $100 B International Space Station gives them time to move out of harms way with very small thrusts.

Mapping space debris can pay for server sky before the first internet antenna is deployed. Like Google's adword auctions, owners of satellites will outbid each other for the first directed searches for orbital hazards.

Thinsats have many redundant frequency sources, which can be calibrated to each other and to ground sources with sub-picosecond precision. Widely spaced arrays can combine coherent transmit beams in a small region of space, producing standing waves, as shown in Fig. 7. If we use high power 60 GHz beams of continuous unmodulated power, the combined arrays can put tens of kilowatts into a distant region a few hundred meters across, and collect reflected power with other arrays optimized for reception. The atmosphere is too turbulent and attenuating for terrestrial radars to do this, and 60 GHz (5 mm) is attenuated by more than 200 dB before it reaches the ground.

As an object traverses the standing wave region, the reflected power changes as it passes through the peaks and nulls. If the object moves at 3 km/s relative to the region created by the orbiting thinsat arrays, the return is modulated at kilohertz rates, and produces a narrow-band amplitude and phase pattern that can be correlated against stored patterns in receive array memory. An array of thinsats can perform billions of correlations per second. It may be possible to locate small objects with centimeter precision, and calculate high accuracy orbital elements to predict their future trajectories for weeks into the future. If we can accurately predict collisions eight hours in advance, we can avoid them with low thrust maneuvers.

This will reduce collisions in server sky arrays, but also make low earth orbit much safer for other assets. It also makes collecting and repurposing debris objects much easier.

XIII. Light Pressure Destabilization

Server sky can actually benefit from space debris, if it is located, collected, and cut into thinsat ballast.

Thinsats are designed for an area to mass ratio of about 5 m^2/kg. We can easily make and launch much lighter thinsats, but light pressure distorts their orbits.

As a thinsat orbits away from the sun, light pressure increases its velocity, and consequently the orbital radius half an orbit later. As it orbits towards the sun, light pressure slows it down and reduces orbital radius on the other side. The orbit pushes towards the earth on the west side of the orbit, and away on the east side.

Because the apparent position of the sun moves around the earth once per year, as the earth orbits the sun, M288 arrays are actually in a slightly elliptical orbit that precesses once per year. The eccentricity (ellipticity) of the orbit increases as thinsats get lighter. The 5 m^2/kg sail ratio was chosen to keep server sky arrays from colliding with the nearest valuable assets, the Lageos geodesy satellites, with an adequate safety margin. Fig. 8 shows the eccentricity needed for different altitudes and different thinsat sail ratios.

A very high sail ratio means less launch weight per thinsat. What if we could launch very high sail ratio, ultralight thinsats,

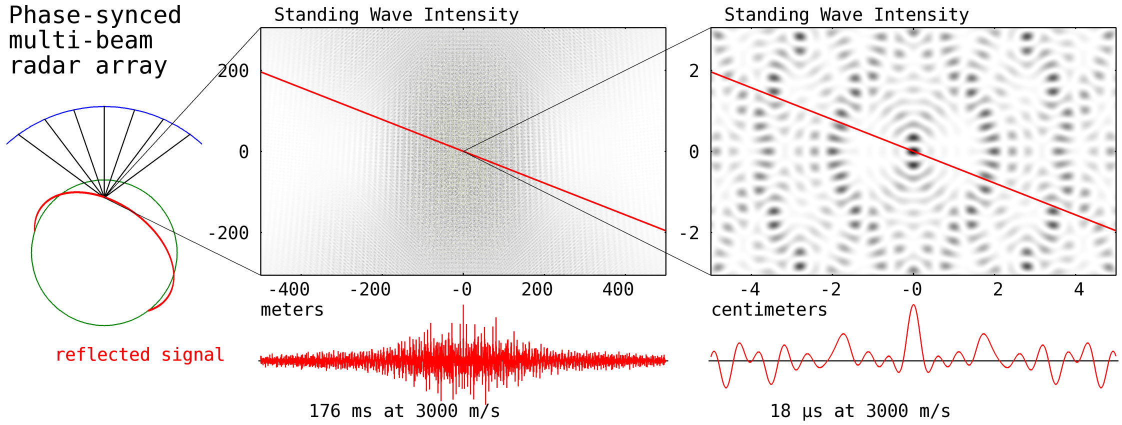

Fig. 7. Interfering coherent beams from many arrays create multi-kilowatt standing waves in a sub-kilometer volume. Debris objects moving through the spatial variation reflect low-bandwidth time-varying signals, correlatable to precomputed patterns. Objects may be located to sub-meter accuracy.

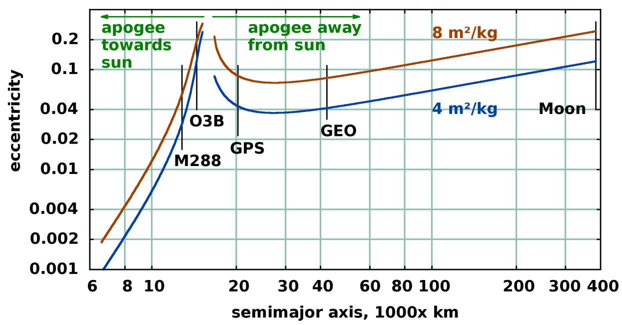

Fig. 8. Eccentricity compensation for light pressure perturbations. Lighter thinsats with more sail area per mass cause more orbit change. At the asymptote in the middle, earth oblateness precession matches the solar year, and light pressure perturbations accumulate without compensation.

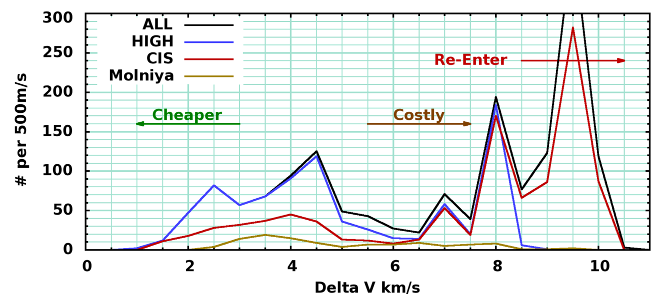

Fig. 9. Derelict rocket bodies suitable for reuse, plotted versus the delta V needed to move them to M288. Some bodies, in highly inclined low earth orbits, are too costly to move to M288, and should be re-entered.

perhaps 16 μm thick, and add 4 grams of additional mass after they are in orbit?

XIV. Capturing Ballast Mass

Orbiting debris is the most accessible high grade ”ore” for space manufacturing in the solar system. Obsolete thinsats, and the rocket stages that put them in orbit, can be cut into ballast mass. Even worn out cutting blades can turn into ballast.

There are thousands of tons of space debris in orbit, much of it upper rocket stages used to boost satellites to their destination orbits. These derelict rocket bodies are a collision hazard, but they can be captured and can be moved to server sky orbit. NASA is developing the VASIMR [24] helicon plasma rocket engine for deep space missions. VASIMR is fueled by sunlight and argon, an inert gas comprising almost 1% of the atmosphere. A space tug using VASIMR engines can move many tons of debris to M288.

Fig. 9 plots the distribution of rocket bodies in earth orbit [26]. The cost of moving objects in space is an exponential function of delta V. Launching a server sky array from earth requires 10 km/s of delta V. Thousands of tons of debris objects can be collected and recycled with less delta V.

Debris in high inclination LEO orbits requires too much delta V to move to M288. This debris can either be de-orbited, or used as collision shielding for the International Space Station. In LEO orbits, electrodynamic tethers [25] can move objects more cheaply than VASIMR.

Thinsat and debris recycling may not occur until many years after the first server sky deployments map the debris environment. However, if we can turn a hazard into valuable material, we can continue to reduce server sky launch costs as demand increases.

XV. Environmental Effects

Thinsats are made with material and energy, an environmental cost. Surprisingly, the energy needed to launch thinsats is small compared to the energy they produce.

A SpaceX Falcon 9 rocket can put 5 tonnes into M288 orbit, one million thinsats. The dry weight is 22 tonnes, mostly aluminum, and the propellant weight is 70 tonnes of RP4 fuel and 210 tonnes of liquid oxygen [27]. Assume an electric-equivalent energy cost of 54 MJ/kg for aluminum, 15 MJ/kg for RP4, and 3.6 MJ/kg for LOX. The energy cost per launch is 3 TJ, or 3 MJ per thinsat. A 3 W thinsat earns that energy back in 1 megasecond, less than 12 days. The same Falcon 9 can take a 15 kW comsat to geostationary orbit, earning back launch energy in 200 megaseconds, more than six years.

The major environmental problem with thinsats is night light pollution. In the very worst case, thinsats might be abandoned in orbit, out of control, tumbling randomly while the thrusters are fully reflective. Perhaps a trillion thinsats abandoned this way might reflect 0.1 lux into the night sky, about 10% of the full moon, with serious repercussions for predator/prey relationships, full moon synchronization of coral spawning, and other known and unknown natural relationships to the dark sky and the moon. 0.1 lux is not nearly as bright as skyglow from a city, but the effects would be felt globally. While three trillion watts of thinsat seems like a lot, we once thought four billion internet addresses was a lot, too. As we grow past a trillion watts of server sky, we should locate new arrays farther out, perhaps beyond the moon, inverse square attenuating the light reaching earth by $4000\times$.

Astronomers demand dark skies, and functional thinsats will orient themselves to scatter far less light than the dark night sky. Thinsats provide 75% power availability rather than the average eclipse limit of 86% because thinsats in the back half of their orbit purposely turn edge-on to the terminator (day/night boundary) of the earth. Any diffuse light they might scatter from sunlight is reflected away from the night sky. Some operators may resist losing 13% of power production in pursuit of dark night skies, especially in the early days when deployments are expensive. Developing economic and legal incentives to do the right thing will be challenging, but these should be enforceable before the first launch.

XVI. Conclusion

From a few small arrays, server sky will grow exponentially. someday replacing ground data centers worldwide, relieving the global grid of their huge energy appetites. In time, we may revisit the old space-power-to-earth dreams, building gigantic terawatt generating arrays to feed the global electrical grid, replacing most terrestrial generation. More likely, we will find new ways to move more of our energy consumption and waste production off the planet; telecommuting to virtual environments rather than driving to work, for example.

The important task is to develop solutions beyond fighting nature and other nations for energy and resources, and begin expanding life beyond the bounds of earth. With the exponential tools of Moore's Law, photolithographic production, and unbounded space energy, we can shrink vast global problems down to human scale. With the internet connecting the entire planet, we can connect any problem to the best minds on the planet to solve it. Together, we can expand life and intelligence to fill the solar system and beyond, while restoring and protecting our precious home, the earth.

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