DISTANT HORIZONS: SMALLSAT EVOLUTION IN THE MID-TO-FAR TERM

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ABSTRACT

ABSTRACT. There are many smallsat missions now in progress or in development, and these are pushing smallsats into new realms of technology, compactness, and mission utility. Proposals for the near term will shrink smallsats further, couple them in new ways using constellations or fractionated architectures, and edge into new mission areas. What, though, is on the horizon looking out 10-25 years or more? While there have been some overly optimistic predictions about smallsats, the advances demonstrated or in development in computing, nanomaterials, microelectromechanical systems, and other areas indicate the future will include some smallsat applications only now being imagined, and others that have not yet been imagined. As once smallsat developers worked with no idea that carbon nanotubes and powerful computers on chips would be available to them, designers of tomorrow will have both evolutionary and revolutionary technologies at their disposal. Ideas that were deemed to push technology too far or cost too much may well be in the mainstream in 2020 or beyond. Some future smallsats will have dimensions measured in millimeters. Some will cooperate in swarms in ways not possible today. Some will be deployed around other celestial bodies or in deep space. Some will perform missions that today require huge spacecraft or cannot be done at all. This paper surveys the leading programs and thinkers in the smallsat realm about what may appear beyond commonly used planning horizons. We have seen 25 years of progress presented at Small Satellite Conferences so far. What might be presented 25 years from now?

INTRODUCTION

The smallsat will turn 54 years old in 2011. Ever since the Soviet Union launched its 84-kg Sputnik 1, the spacefaring world has known that important missions can come in small packages. While the average size of spacecraft grew enormously, smallsats from Transit (navigation) to MacSat (communications) continued making contributions. A new wave of miniaturization began about 20 years ago and never stopped. Now we have 1-kg CubeSats, science craft the size of bread loaves, and ever-shrinking applications satellites (including imaging satellites, once thought to be unshrinkable). On the drawing boards are cooperating constellations, fractionated architectures, tiny "PocketQubs," and swarms of satellites built on individual computer chips. What lies beyond the near horizon? Are there firm limits to what can be done by smaller, lighter satellites, and are we anywhere near those limits?

Form and Function

Spacecraft sizes are dictated by several factors, ranging from budgets to physics. Smaller is often better because it means reduced spacecraft and launch costs, but that's only a general rule: there are always tradeoffs, and sometimes the rule fails. Sometimes technologies enable new missions, and sometimes mission specifications drive technology. It's vital to understand technology, missions, and the factors bearing on both to develop a picture of microspace in 2020 and beyond.

This paper focuses on satellites under 100kg. We use the prefix "micro" for all spacecraft under that mass limit and "nano" for the subset from dust size to 10kg.

Promise and Performance

Since the "microspace revolution" began, some predictions of what microspacecraft would do in what time period have misfired. Overenthusiasm led to some unfulfilled expectations (although many prospective breakthroughs were not tested and found wanting, but were merely unfunded). Some spacecraft, like geosynchronous communications satellites, have even gotten larger in the last few decades. Making projections about the future of microspacecraft requires a mix of extrapolation from current work plus educated guessing, but it can be done, and it can give us an important glimpse into the future.

THE ADVANCEMENT OF TECHNOLOGY

How Far and How Fast

Microspacecraft technology has advanced enormously over 54 years, and particularly in the last two decades. The pace of change is, if anything, accelerating. Space and defense organizations around the world are bringing new resources to microsat development, and that has important implications for post-2020 developments as well as current ones.

Microsats have always had their place, albeit often uncredited, in projects ranging from the first weather satellite to the first probe to orbit another celestial body (the 36-kg Apollo-launched Particle and Fields (PFS)-1 microsat, which orbited the Moon in August 1971).

The first firm dedicated to microsats, AeroAstro, was founded by Dr. Rick Fleeter in 1988. One of its ideas, Bitsy, was a "kernel" with computer, communications, and power systems, to which other elements of a modular satellite could be connected. Fleeter projected getting this capability on a single chip by 2000. This proved too optimistic, but today the pieces of this vision are coming together. Air Force Research Laboratory (AFRL) has developed a plug-and-play (PnP) standard called Space PnP Avionics (SPA), and researchers at Cornell University and elsewhere are testing "chipsats" which include not just the kernel but the entire satellite.

Another Fleeter idea was ESCORT, "a tiny piggyback satellite that will be released from the main satellite bus and inspect the main satellite."[1] In 2000, the U.K. microsat firm Surrey Satellite Technology Ltd. (SSTL) launched SNAP-1, a 6.5-kg spacecraft that maneuvered around and imaged the larger Tsinghua-1 microsat. This was the first satellite in its weight class with three-axis stabilization, important to missions like imaging as well as inspection. In the United States, Air Force Space Command (AFSPC) has tested inspection microsats with its XSS-10 and XSS-11.

By the mid-1990s, the National Aeronautics and Space Administration (NASA) joined in with its New Millennium Program (NMP), with small space probes which tested new technologies such as ion thrusters. Rex Ridenoure, an engineer with NASA's Jet Propulsion Laboratory (JPL), suggested microlanders "to cheaply get something under the surface of Mars." Another NASA concept of that era was space-based interferometry with three smallsats in formation creating a baseline of tens of kilometers, acting as a single unit to image planets circling distant stars.[2]

NASA tested the planetary microprobes idea with the NMP's Deep Space 2, which launched in 1999 with two 2.4kg probes to be released from the Mars Polar Lander to punch into the Martian soil. The probes were deployed from the ill-fated Lander but failed to survive descent. (The failure was attributed to inadequate testing, not any inherent problem with the concept).[3]

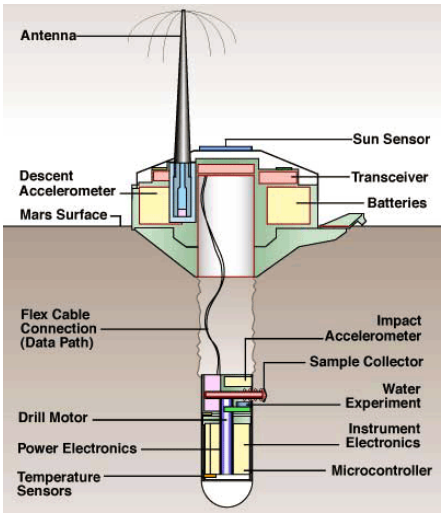

Figure 1. Deep Space 2 Mars microprobes (NASA)

Also in the mid-90s, Henry Helvajian at Aerospace Corporation suggested that microelectromechanical systems (MEMS) would soon enable 1-kg nanosatellites, allowing for mass production and huge constellations of communications or Earth observing satellites.[4]

Helvajian and his organization followed up by producing the first MEMS-enabled satellites, a pair of 250-gram PicoSats connected by a tether, in 2000. These super-miniature craft were ejected on orbit by the 23-kg Orbiting Picosatellite Automated Launcher (OPAL) and were tested successfully. More such satellites were deployed from the Air Force's MightySat II.1 in 2001, and two pairs of slightly larger MEMS-enabled PicoSatellite Inspector (MEPSI) satellites, which added a propulsion capability, were deployed from Space Shuttle flights.

By 1996, leaders at AeroAstro, Spectrum Astro, and other smallsat firms anticipated nothing but smaller and cheaper. W. David Thompson, president of Spectrum Astro (now part of Orbital Sciences Corp), said, "We will see the continuation and acceleration of the trend toward smaller satellites. It's the only solution with the economic situation most customers have, both government and commercial." [5]

A decade later, many of the projected ideas had been space-tested. Some were tested on CubeSats, 1-kg, 10x10x10-cm cubes which first flew in 2003 and provided a cheap standardized bus which could be

customized or combined in two- and three-unit (abbreviated 2U and 3U) buses.

In 2006, microspace advocate Dr. Simon "Pete" Worden was named to head NASA's Ames Research Center. Ames was soon examining tiny science spacecraft, which would soon lead to the 5-kg GeneSat and PharmaSat Risk Evaluation Satellite (PRESat), using 3U CubeSat buses. (The former flew in 2009, while the latter, which would have studied the growth of yeast cells in orbit, was lost in a 2008 launch failure.)

Also in 2006, NASA Administrator Michael Griffin told the 20th Conference on Small Satellites that he'd like to see NASA do more small satellite missions and that they, not large satellites, would best serve as communications and navigation infrastructure in the inner solar system. "It's much better to have a network of small satellites doing the same thing--each of them having an IP address or the equivalent ... that's available at the click of a mouse button."[6]

Five years later, this and other proposals for far-reaching data and navigation networks remain unfunded, in large part because of the lack of firm plans for the human exploration they would support.[7] However, the agency Griffin used to run has continued to fund downsized science craft. NASA's Ames Research Center has been the most active locus, but smallsat missions have been developed or supported by several other centers.

RECENT TRENDS AND MAJOR PLAYERS

U.S. Defense Agencies

The Department of Defense (DoD), owner of the largest space budget of any organization in the world, has been instrumental yet sometimes ambivalent about microspace. Services and agencies under DoD (especially the Defense Advanced Research Projects Agency (DARPA)) have funded many of the breakthroughs in microsat technology, but have been hesitant about putting the results to operational use and are still debating how much utility microsats offer.

In 2007, DoD created the Operationally Responsive Space (ORS) office at Kirtland Air Force Base (AFB), NM. While ORS is broader than microsatellites, smaller and faster space capabilities were part of what General C. Robert Kehler called a "national strategic capability for the ability to augment or supplement" larger space systems.[8] ORS satellites so far are in the 400kg range, well out of the microsat class, but they do represent a sharp decrease in the size of military satellites providing operational capabilities, notably multispectral imaging. The organization is examining the utility of much smaller satellites, including CubeSats.

As of 2011, smaller satellites are being examined as part of a concept the Air Force Space Command (AFSPC) commander, General William Shelton, has endorsed to consider "disaggregating" major payloads, breaking them up among more satellites and hosted payloads to improve resilience. While DoD's satellite architectures are already locked in for the next 10-15 years, that stability means "an opportunity right now to start to turn this ship" toward disaggregation.[9]

AFRL's Advanced PnP Technologies (APT) satellite, (a.k.a. TACSAT-5) will test Honeywell's Mini-MCS, a plug-and-play momentum-control system. AFRL believes its SPA standard will allow rapid assembly, test, launch, and on-orbit checkout, all in a matter of days, which would cut costs drastically by reducing the manpower requirements of developing a space mission. SPA satellites are not flying yet, since the initial development of components to meet a new standard, even one aimed at simplifying assembly, is itself a complex undertaking.[10] However, AFRL let six contracts in 2009 for SPA development, and one company will be picked to launch the APT in 2015.[11] SPA is not the only standard proposed (the Standard Interface (SIF) from the SpaceQuest Canada is just one of several examples), and it may be some years before "winning" standards can have their full effect.

In January 2011, the Army Space and Missile Defense Command (SMDC) launched the 5-kg SMDC-ONE, first of a series of eight planned nanosatellites (the eight having already been delivered by Miltec) to demonstrate possible operational capabilities. In a 35-day mission, it served as a communications relay for text and images from ground sensors. SMDC is planning to orbit three more satellites in 2011-2012.

SMDC is also pursuing an imaging satellite called Kestrel Eye, weighing only 14kg but with a resolution of 1.5m. SMDC views nanosats as an important niche where spacecraft can be built for hundreds of thousands of dollars on short timescales and operate covertly (such satellites are extremely hard to spot optically or by radar). The Army may continue a nanosatellite program long-term to provide soldiers with capabilities DoD's large satellites don't cover.[12] This effort could be coupled with the Army's planned Multipurpose Nanosatellite launcher, being designed by COLSA and Dynetics, which is intended to provide $1M launches using a single liquid-fueled stage with strapon motors from existing missiles.

Even the National Reconnaissance Office (NRO), known for bus-sized imaging satellites, created a

CubeSat office called Q_bX. The NRO bought an initial lot of 12 CubeSat buses, although the agency is characteristically tight-lipped about what technology will fly on what it calls the Colony 1 nanosats. The first two satellites already launched with the Army SMDC-ONE: the others will go together on a SpaceX Falcon 1e booster. (That SpaceX booster also carried four CubeSats with an unknown mission for Los Alamos National Laboratory[13].) NRO also contracted with Boeing Phantom Works for 10 satellites, with plans for up to 40 more. These Colony 2 spacecraft will be 3U CubeSats with improved pointing capabilities and more electrical power.[14] The NRO did created the Innovative Experiments Initiative (IEI) to find partners for CubeSat-based experiments. Over 70 partners have signed up.[15]

Nondefense Players in the U.S.

NASA, the world's largest civil space agency, has continued to ramp up its interest in microsats and microprobes. NASA's Astrobiology Science and Technology Instrument Development program created a nanosatellite initiative in 2008, with the sophisticated 3U CubeSat O/OREOS (cost: $2M), with two biological experiments aboard, selected as the first project.

In December 2010, NASA ejected the NanoSail-D2 nanosatellite, a 3U CubeSat design, from another satellite. Such deployments reinforce the potential, displayed earlier in the PicoSat and MEPSI projects, of kicking tiny satellites or probes off larger ones as needed. NanoSail-D2's deployment of a solar sail of $10m^2$ demonstrates a method future nanosats could use for propulsion or deorbiting. (NASA learned from NanoSail-D2 that such a sail is effective in deorbiting, although the descent is lower than expected, as the sail went into a flat spin rather than holding a maximum-drag attitude.)

NanoSail-D2 is also noteworthy as a reminder of one important feature microsats offer to budget-constrained researchers: the possibility of building affordable backups or replacements. NanoSail-D2 was built after the first NanoSail-D was lost in a launch failure in 2008.

A Worldwide Phenomenon

Microsats have often been a gateway to space for nations seeking to orbit their own satellites, from Sputnik 1 in 1957 to Iran's Sina-1 in 2005. They are often the first type of satellite built in a nation, with much of the credit going to the CubeSat wave. Over 100 organizations, many educational, have participated in CubeSat development. A quick Internet scan of CubeSats planned for launch in the next two years shows researchers in Ecuador, Peru, Hungary, and Vietnam are preparing their nations' first home-built satellites. These are not simple beacons, but real spacecraft testing real technology and doing real science.

Global interest in small spacecraft, though, encompasses much more than CubeSats. In one of the most interesting examples, the European Space Agency (ESA) is following the progress of its miniature cometary lander, Philae. Philae was launched in 2004 with its parent spacecraft, Rosetta, to rendezvous with Comet 67P/Churyumov-Gerasimenko in 2014. Ten science experiments are packed into the 100-kg lander.[16] The SSTL-built Disaster Monitoring Constellation (DMC) has been providing imagery through since 2002 through microsats operated by the space agencies of Algeria, Nigeria, China, Turkey, and the U.K. Operated by DMC Imaging International, the DMC is a highly successful microsat-driven model for future cooperation.

At the 2011 meeting of the United Nations Committee on the Peaceful Uses of Outer Space, delegates recognized the way microsats were democratizing space on a global basis and created the Basic Space Technology Initiative (BSTI) to further this trend with conferences, fellowships, educational programs, and backing for international microsat projects. One of the first BSTI-backed ideas is HUMSAT, an effort led by the University of Vigo in Spain to build a constellation to gather data from sensor networks around the world.[17]

Making Microsats

Most microsats are built largely by hand, but satellite manufacturers have been exploring approaches that could result in easily producible, highly capable future generations. Microsats have been built in groups, the largest example being the 43 Orbcomm-1 comsats in the 1990s.

AFRL asked Space Dynamics Laboratory (SDL) in 1999 to take a look as manufacturing 100 on-orbit servicing microsatellites. SDL produced the Advanced Space Technology (ASTEC) design and a plan to combine a number of advances and techniques to move to platform architecture (use of a set of subsystems supporting a variety of satellites). SDL proposed mass-producing parts by ultrasonic consolidation (UC) (using ultrasonic welding to make components in an additive process from metal foil). UC can also be used to embed fiber optics and other components in substrates, and SDL's plan also included Direct Write (DW), a process developed with DARPA to "write" circuitry on components without the need for tooling.[18] While no

mass production orders for such microsats have yet been placed, elements of this approach, along with advances produced by Aerospace and other hardware firms, have been continually introduced into satellite building.

On the Drawing Boards

Numerous technologies with promise to further shrink spacecraft are being readied for flight in the next few years.

Prof. Twiggs, now with Morehead State University, points out that the continued shrinkage of technology will enable new research, not just on free-flying satellites, but also on microlaboratories aboard the ISS, reusable spacecraft like SpaceX's Dragon, and future platforms.[19]

The ExoplanetSat, an MIT/Draper planet-hunting mission described in more detail below, is one concept taking advantage of the microspacecraft's ability to be made and launched in significant numbers. Another is the international QB50 mission, which in 2013 will place 50 space-weather nanosats, each built into a 2U CubeSat, into the lower thermosphere.[20]

The U.S Army's Small Agile Tactical Spacecraft contract, awarded in 2010, covers development of a nanosatellite capable of transmitting 2m imagery in real time to soldiers in a theater of operations. The Army and Andrews Space envision a constellation covering a revisit rate under ten minutes.[21]

Microsatellites for on-orbit servicing or deorbiting of larger satellites have been investigated at least since SDL produced the 40-kg ASTEC design for AFRL. As complex satellites in the range of a few hundred kilograms, like the U.S. military's TacSat and ORS series, are built, and the orbital debris problem gets worse, look for both options to be revisited. NASA's 2011 Edison solicitation listed on-orbit servicing as one application for which NASA wanted to see new microsatellite proposals.

Testing Future Technologies

Ideas for further advances in spacecraft technology are as numerous as CubeSats. (Many new technologies, indeed, are being flown on CubeSats.) Only a few examples can be given here.

To give one example, 2009's BEESAT from the Berlin Institute of Technology packed a CubeSat with six sun sensors, three gyros, two three-axis magnetic field sensors, six magnetic coils, and three reaction wheels to test miniature fault-tolerant attitude determination and control technology.[22]

The low-cost technology testing possible with nanosatellites has attracted even the aerospace giants that normally build satellites weighing tons. A SpaceX Dragon flight in 2011 deployed the Mayflower CubeSat, a commercial project by Northrop Grumman in concert with Applied Minds and the University of Southern California to fly components including "a new, previously unproven advanced solar cell deployment system."[23] Boeing has also flown nanosatellites, starting with CubeSat TestBed 1 (CSTB1) in 2007. Boeing plans to use multi-unit CubeSats to further test its own technologies in addition to supplying CubeSat-based satellites to customers (already having sold a batch to the NRO). Lockheed Martin Space Systems Company has joined the Colorado Space Grant Consortium in developing a 3U CubeSat, the Agile Low-cost Laboratory for Space Technology Acceleration and Research (ALL-STAR).

Sweden's ÅAC Microtec, with Swedish and German partners, launched their 8-kg RubinSat 9.2 payload in 2009. While this payload was not a free-flyer – it went into orbit on the fourth stage of an Indian PSLV booster – Microtec advertised it as the first microsatellite to use 3D-wafer microelectronics and MEMS to deliver, in 120 grams, a computer, control systems, and mass memory on a satellite designed with a plug-and-play approach.[24]

Scaling Down

The answer to "how small can we go?" is complicated because some things scale and some don't. There are limits to how small any functional device can be, and, while those limits are constantly being pushed by nanotechnology, it's not a simple matter of shrinking to infinity.

Satellites which require active thrust need some form of propulsion system along with fuel. Fuel implies bulk, a problem still being tackled, not only with miniaturized chemical thrusters but with ion and other drives, which for very tiny satellites can include exotic notions like the use of electrostatic forces to accelerate interstellar dust. A 2009 paper counted 15 available or possible thruster types.[25] A recent study by JPL researchers focused on propulsion options for CubeSats described four practical near-term types (cold gas, butane, pulsed plasma, and the vacuum arc thruster), with miniature ion thrusters and microfabricated eletrrospray arrays as promising concepts on the horizon.[26]

To these options we can add electrodynamic tethers. The Naval Research Laboratory (NRL) will fly a mission in 2012 to demonstrate that, by varying the current in a conductive tether between two microsatellites, a satellite can "ride" Earth's magnetic

field and raise, lower, or even change inclination of its orbit. Larger missions with more links and longer tethers will follow. The force involved, according to Director Pete Wilhelm of the NRL's Naval Center for Space Technology (NCST), is less than 1 newton, but it can be applied continuously for as long as it takes to move the tethered system. Such a linked system may seem clumsy, but it has its advantages. Cameras or other instruments on microsatellites a kilometer apart can provide stereoscopic data on a satellite, planet, or other target of interest.[27]

Antennas and other electromagnetic devices are scaled to particular wavelengths. Such devices, including communications and optical sensors, can be made only so tiny on an individual satellite. This requirement for aperture, however, may be avoided with clusters of cooperative microsatellites forming "virtual apertures."

There are tradeoffs to everything: microsats that can form virtual apertures may still have minimum size limits, since cooperation requires each satellite have, as a minimum, a communications system and some means to keep station with others. There is some possibly engineers may even design their away around that requirement: Microcosm's "structureless space telescope" idea includes using light pressure from free-flying lasers to keep tiny mirror nanosatellites in the proper position.[28]

Almost all scientific instrumentation has shrinkage limits, although clever design and new technology keeps revising those limits downward. For example, a growth chamber, monitoring equipment, and an environmental control system are needed to study the growth of microbes in space, and all that was packed into NASA's 5-kg Organism/ORganics Exposure to Orbital Stresses (O/OREOS) nanosat.

Thermal control can be difficult, too, as satellites shrink: microsatellites pack electronics into a very small space, and heat must be dissipated. Likewise, most satellites can't perform a function without onboard power, usually solar cells or batteries.

Prof. Robert Twiggs, inventor of the CubeSat with Jordi Puig-Suari of California Polytechnic State University, notes that the miniaturization of commercial electronics was the technological foundation for tiny satellites. Without that, the power provided by solar cells on a CubeSat-sized satellite couldn't run the electronics.[29]

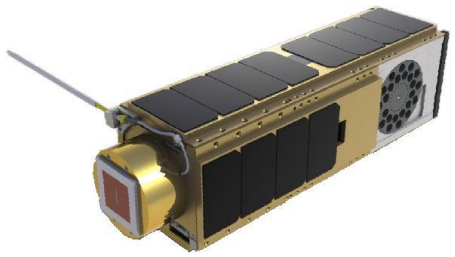

Figure 2. NASA's 5-kg O/OREOS, a biological testing laboratory launched in 2010. (NASA)

Dr. Griffin estimates that satellite electronics have historically lagged consumer electronics by a decade, but this is still a rapid rate of innovation, and the lag may be shrinking. Experimenters have already tested Android™ smartphones as payloads on sounding rockets and near-space balloons. Surrey engineers will soon launch STRaND-1, a 4-kg satellite built of off-the-shelf components with an Android™ serving as flight computer (a more conventional microcomputer will test out the smartphone, then shut down and hand over the satellite to the Android™.)[30]

Efforts continue to drive down the size and increase the efficiency of satellite systems. In 2009, Aerospace built the 10x10x25cm Picosatellite Solar Cell testbed, which had four cameras and also tested mini-sun sensors, Earth sensors, and attitude control. A successor will go into a high elliptical orbit to stress components further by going through the Van Allen belts. The NRL, which has been in the microsat business since Project Vanguard began in 1955, is working on solving another problem: miniaturizing secure communications devices, essential for many defense applications. The NRL helped NRO fly two experimental communications nanosatellites, Q_bX1 and Q_bX2, in late 2010.

Other developments already improving the utility of microspacecraft include advances in the efficiency of solar cells, the energy density of batteries, and the availability of increasingly light and strong materials such as carbon nanotubes.

THE MISSIONS OF MICROSPACECRAFT

The paragraphs above give a good overview of the missions proven possible so far by microsats that made it to space or soon will. In the applications arena, we have communications, imagery, electronic intelligence (pioneered by the CERISE microsat built by SSTL for France), weather, space weather, navigation, tracking of trucks and shipments, monitoring of ships via the Automatic Identification System (AIS), and every kind of Earth science. Microspacecraft have performed

space-based astronomy and sent back information on the magnetosphere, the Moon, the Van Allen belts, asteroids, and other celestial bodies.

In early 2011, Axelspace of Japan organized a Nanosatellite Ideas Competition. The winners give some examples of current thinking on the utility of very small spacecraft.[31] Three of special interest are:

1) Mitsubishi Electric's Integrated Meteorological / Precise Positioning Mission Utilizing Nano-Satellite Constellation would combine 15-kg nanosatellites observing the radio occultation of the Global Navigation Satellite System (GNSS) from edge-on with 14-kg nanosatellites acquiring thermal infrared images from the zenith, resulting in more precise local weather forecasting and precise positioning information unaffected by atmospheric conditions.
2) MIT's ExoplanetSat Constellation, dedicating an initial fleet of 24 5-kg satellites with optical detector arrays "to monitor each of the brightest Sun-like stars for Earth-sized transiting exoplanets." This idea is already progressing: the first wave begins launch in 2012, with a more sophisticated second wave in 2014.
3) Surrey's Distributed Multi-Spectral Imaging System (DiMSIS) would, for $6M, deploy 15-kg nanosats for medium resolution (<32m) multispectral imagery, with a development time of two years and responsive (1-year) augmentation and upgrade.[32]

NASA, as part of its new Space Technology Program, is also pushing ahead on new microsat ideas. Its Edison Small Satellite Missions Program will develop a series of NASA-focused small satellite demonstration missions, while the Franklin program will test innovative technologies enabling such missions.

Reaching Beyond Earth

Microprobes into the atmosphere or surface of other worlds are becoming increasingly practical. As far back as 1978, Pioneer 13 dropped three successful 75-kg probes (and one larger one) into the atmosphere of Venus. Recent microprobes have hit an unlucky streak: the United Kingdom's Beagle 2, a 33-kg Mars lander, succumbed to an unknown failure in 2003, and Japan's 0.6-kg MINERVA "hopper" was apparently released by the Hayabusa probe on the wrong trajectory to the asteroid Itokawa in 2005. Even the failures, though, have helped refine technology and procedures for future missions. Hopefully the Philae lander will mark a return to success for miniature explorers and boost the similar concepts now being proposed.

Cornell University researchers are working on another aspect of technology: reducing the size of nanosatellites still further. They believe their Sprite, a stamp-sized satellite-on-a-chip now being tested with three units mounted on the outside of the International Space Station (ISS), can be developed into a swarm of craft that could sail on the solar wind into the atmosphere of Saturn.

The Philosophy of the Future

Jordi Puig-Suari of California Polytechnic State University, who developed the widely used Poly Picosatellite Orbital Deployer (P-POD) which helped popularize CubeSats, believes that shrinking a large spacecraft isn't the right way to think about microsats. "For organizations with limited resources, which can't buy or build large satellites, it's 'Okay, what can I put inside that box?'"[33] What goes inside the box today will go in a smaller box tomorrow, and organizations that cut their teeth on small satellites will find themselves capable of a range of approaches.

No one expects microsatellites, even advanced cooperative clusters, to perform every function. As Prof. Twiggs put it, "Everybody doesn't drive a little teeny car; there are big trucks to carry things around."[34] Just as PCs and smaller computing devices have not caused the disappearance of servers and supercomputers, any future space architecture has room for both "battlestars" and microsats.

Microspace projections have to be tempered with cautions drawn from the field's history so far – spectacularly successful though it's been. Dr. Jim Wertz of Microcosm, a pioneer in this field, doesn't think enthusiasts have overpromised on the potential for microsats – no more, he notes, than proponents of other space technologies. Some things just haven't been tested yet.[35]

Not everything can be done with microsats, and not everything that can be done on the microscale will be, or should be. For instance, it may be that a constellation of tiny mirror-satellites acting as an optical telescope aperture and controlled (physically or by advanced image-processing software) to within a fraction of wavelength of visible light is practical. But we don't know yet whether this will prove cheaper or easier than launching a traditional large mirror. (Surrey and JPL are investigating another approach to this particular problem, where small spacecraft physically join up on orbit to make a large mirror).[36]

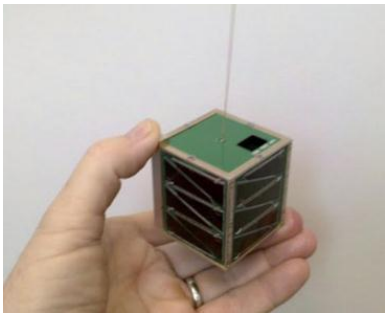

Figure 3. "PocketQub" satellite. (Robert Twiggs)

SOLVING THE LIMITS

Microsats have leaped from "toys" to the mainstream, sometimes slower and sometimes faster than expected. Coordinated multi-satellite apertures have developed slower than hoped but now look more promising, while applications involving miniature instrumentation and electronics have moved very quickly.

The Limits to Shrinkage

Prof. Twiggs sees the current baseline, CubeSats, shrinking much further. The PocketQub is a 5-cm satellite (1/8 the volume of a CubeSat), ready for missions now. The TinySat, or Moonbeam, is an educational satellite of which 24 can fit in a CubeSat volume. Twiggs sees these as satellites for middle or high school students. They could be released in a swarm to send back data from dozens or hundreds of points, or released from a Moon-bound craft and use lunar gravity to launch themselves on a swing by Earth and then into deep space. Interorbital Systems is selling kits for 0.75-kg "TubeSats," advertising the kit plus launch at $8,239.[37]

There are some special problems which come into play when tiny spacecraft venture far out into the solar system. Cosmic ray shielding is hard. Antennas and solar panels are increasingly difficult to miniaturize as the spacecraft gets further from Earth and from the Sun. Part of the solution is mission design. The Deep Space 2 Mars microprobes had low-power radios and simple antennas to send their signals to the orbiting Mars Global Surveyor to relay data to Earth. The aforementioned interplanetary networks, while they are not yet on any agency's launch schedule, could eventually enable low-power microspacecraft to "plug in" from countless destinations. Radioisotope thermoelectric generators (first tested in space on the 78-kg Transit 4A satellite in 1961) or the kind of plutonium batteries formerly used in heart pacemakers may be options (albeit controversial ones) on deep space missions.

Miniature imagers have advanced enormously, but they do have an end point: the diffraction limit and the technology of annular folding optics will hold a microsat with a 20cm aperture to resolution of 2.5m from 500km, which is amazing in itself and fine for many applications.[38]

There are also special concerns which may limit the continued shrinkage of microsats. Chief among these is the debris problem.

Cleaning Debris or Causing it?

The USAF tracks some 22,000 space objects and estimates there are hundreds of thousands more. On the one hand, microsats have less chance of colliding than most satellites, since they present less frontal area. On the other, they pose a hazard by being, in some cases, too small to track. A CubeSat crossing orbits with a largesat could put both out of commission. As with all satellites, microsats' lifetimes depend on the orbit: NASA's 5-kg GeneSat-1, with an initial apogee of 415 km, lasted under five years, while the 1958 microsat, Vanguard 1, will be up for centuries. One intriguing possibility concerning plans for cheap, mass produced microsats is the ability to accept shorter lifetimes and avoid debris problems by orbiting at 200km or lower. SMDC-ONE, placed in an orbit of 247x229 km, lasted only 35 days. Another potential solution is s standardized transmitter or transponder so an otherwise untrackable satellite can announce its own position.

Given that microsats generally have shorter active lives and far less onboard propellant than largesats, tighter regulations on debris creation expected soon mean that mission designers need to be imaginative in their deorbit strategies. Inducing drag with a variant of NASA's NanoSail-D is one option. The NRL, working with the company Tethers Unlimited, is planning missions where electrodynamic tethers stretched between microsats will be the solution, not the problem. Simulations indicate 12 groups of microsats, each spanning 10 km along their tethers, could be equipped with netting and remove all the trackable debris from LEO in a seven-year mission.[39]

LAUNCH: MISSION IMPOSSIBLE?

There is no way to address the future of microspacecraft without addressing launch. The launch options we develop will have a great influence on how that future unfolds.

Secondaries and Primaries

Microsats lend themselves to more launch modes than larger satellites: riding as secondary payloads, launching in quantity on a shared launcher, or tossed

overboard from the ISS. This has not meant smooth sailing for those seeking launch, but there are helpful programs: the Space Flight Laboratory of the University of Toronto coordinates multi-CubeSat launches on Indian and Russian vehicles under its Nanosatellite Launch System (NLS) program. NASA has a CubeSat Launch Initiative and regularly provides launch opportunities for CubeSats as secondary payloads on NASA launch vehicles.[40] DoD's Space Test Program (STP) has long been making similar arrangements, although only a minority of the experiments approved by the affiliated Space Experiments Review Board (SERB) can be accommodated this way.

Many small launcher projects have failed to raise money or vanished when an initial flight test failed. Others, notably Pegasus and Falcon 1, resulted in successful boosters, although the flight rate has always been lower than expected and keeping costs under the $10M mark has proven elusive. Dr. Doug Beason, Chief Scientist at AFSPC, believes we need a launcher costing $1-2M, which would bring a microsat launch vehicle cost closer to the value of the payload and thus much more practical economically.[41] (A cheap, responsive microsat launch vehicle of that kind is referred to hereinafter by the generic term MLV).

Quest for the MLV

So far, technology and economics have conspired to keep a true MLV been out of reach. Arguably the only such vehicle launched was the U.S. Navy's 1958 NOTSNIK, a 930-kg air-dropped rocket that provides a limited proof of concept. NOTSNIK, however, was a marginal design given the technology of its day. That and insufficient time and money for testing meant it orbited its 1-kg satellite between zero and two times (satellite tracking was in its infancy) in six attempts.[42] Russia's Shtil, a converted submarine-launched ballistic missile with a 160-kg payload capacity, is the closest international example: it's a very low-cost vehicle (the first customer paid under $150,000, the second under $2M), but it has flown only twice, and American microsats in particular face export rules difficult for small institutions to deal with.

Dr. Griffin cautions that the business case for investing in that technology may never work. Scaling down orbital launchers is a difficult challenge (payload mass fraction generally declines with the size of the booster) and may not be possible, or may not be worth the money and manpower required.[43] Others, such as Dr. Peter Wegner, Director of the ORS office, thinks it may be possible but that not enough resources have been applied because MLVs would not be highly profitable. He and Dr. Beason, along with the leaders of private launch firms, express hope that government intervention can get companies through the R&D phase and into production of an MLV, at which point the manufacturers could make money selling large numbers of launches instead of needing a large profit on every launch. Whether this concept will work technically or financially remains to be determined, but serious efforts are underway.

Taking Another Shot

AFRL is funding $32M in research related to MLVs.[44] NASA's 2010 "Nano-Satellite Launch Challenge," which offers $2M for launching a 1-kg payload to orbit twice in one week, is another effort spurring companies trying to crack this nut. NASA's Challenge is particularly interesting because the one-week requirement mandates fast, efficient launch support operations: one problem with today's vehicles is that a launch may take many months or years, and organizations with small budgets can't always keep their teams together over such a period. (Accomplishing this on current large-rocket ranges would require the transformation of launch and range operations, a topic beyond the scope of this paper. This is one reason many potential MLV builders like air-launched concepts.)

For example, Generation Orbit Launch Services is working on its air-launched GO Launcher, a 10-30 kg to LEO payload system, and Garvey Space is flying suborbitally as it works toward its orbital launcher.[45] Other companies still trying to make this idea work include Interorbital Systems, Starfighters, Microcosm, Sierra Nevada, Spaceflight Services, and Advent Launch Services.[46] The Army-sponsored NanoMissile System (MNMS) (not funded yet for development), is intended to put 10kg in orbit for $1M.

Suborbital space tourism companies are also looking at providing microsat launch with expendable upper stages. Virgin Galactic proposes to air-launch small satellites from the White Knight 2 built to launch their suborbital tourist craft, and other suborbital operators have looked into the prospect. (Dr. Wegner notes that White Knight 2's home field in New Mexico is only 240 km from Kirtland AFB, home of both ORS and the AFRL's Space Vehicles Directorate.)

With all this attention, the MLV problem may yet be solved. Microcosm's Wertz, who has seen many efforts (including his own company's) fall short so far, still believes renewed interest in microsats will lead to a solution in the next decade. Or it may be that secondary payload launches will, as now, be predominant.

Secondary payload opportunities have limits, given the need to work with the spare capacity, orbit, and schedule of the main payload and the reluctance of payload and vehicle operators to complicate their missions (the ESPA ring, capable of carrying microsats on every U.S. Atlas V or Delta IV flight, has done so only once, in 2007). As Dr. Beason observes, the need to wait months or years for a launch has greatly retarded the utility of microsats, especially from a military point of view, because responsiveness is one of the key things microsats can offer.[47]

With no proven MLV, the current situation will hold for at least a few more years, meaning secondary rides will continue to be the predominant near-term approach to orbiting microsats. While this is not a satisfactory situation (there is a growing backlog of SERB-approved experiments waiting for STP flights), it still makes sense to pursue standard interfaces and other efforts to make secondary payloads a simpler and more affordable option, even as work goes on toward a hoped-for breakthrough in the MLV field. In one positive development, a new type of dispenser set to fly on an ORS/NRO launch of SpaceX's small Falcon 1e booster will be able to dispense 24 single CubeSats or eight 3U spacecraft, and more than one such "wafer" can be on a flight.[48]

One possibility for improving the secondary payload solution is to improve propulsion technology for microsats, allowing for a greater range of orbits once they are ejected from their boosters. The studies and tests already mentioned in this paper include a total of 16 options for microsat propulsion. Dr. Wertz suggests there's a great deal of room for applying these improvements, as miniaturization of payloads and bus components will leave a larger fraction of satellite mass for propulsion. This development, he believes, could allow microsats to offer a change in velocity (Δv) of hundreds of meters per second.

LOOKING FORWARD

One sign a field of technology is gaining traction is the proliferation of related conferences where knowledge (and encouragement) can be shared. In addition to the 25-year-old Conference on Small Satellites, Boeing hosts the GAINSTAM (Government and Industry Nano-Satellite Technology and Mission) Conference. Others include CubeSat conferences and sessions, the Responsive Space (now Reinventing Space) Conference, and the Commercial and Government Responsive Access to Space Technology Exchange (CRASTE) conference focused on cheap small launch. All these will contribute further to sharing ideas about new technology and new missions. The United Nations Office for Outer Space Affairs is helping organize more conferences in more nations under the aforementioned BSTI. Small satellite conferences have met for years in Europe and Canada. India held its first microsatellite conference in 2010, and Japan now has its own as well. This is far from an exhaustive list.

The club of nations with spacecraft grew very slowly until the 2000s. Two particular events, Surrey's export of microsatellite buses and expertise to many nations and then the CubeSat explosion, created a tipping point, making the number of organizations working in satellites – and thus the technological, financial, and other resources available for space missions – "go nova." Microsatellites can be visualized as the ever-expanding core within that nova. This global participation, and the expertise being developed through it, ensures microsatellites are not just on another of their periodic waves of popularity. They are a solid and certain part of the future in space.

Neither missions nor technology exists in a vacuum (even when, technically, they do). New missions can arise from imagining the use of emerging technology, or missions may be imagined and then technology developed to enable them.

Dr. Rudy Panholzer, who has been developing small spacecraft at the Naval Postgraduate School since the 1980s, notes there are two kinds of trends in microsat evolution. Some, like the continuing shrinkage of hardware, were extensions of current technology trends and would inevitably be applied to satellites. Others, like fractionated architectures and the combining of satellites to form virtual apertures, were conceptual breakthroughs.[49]

The Future Speeding Towards Us

After the explosive advances in microspace technology in recent years, what missions and applications will we really see, and when?

James Cantrell of Strategic Space Development Inc. suggests CubeSats and their smaller cousins will alter the satellite business by creating "a strong bifurcation between the "little" and the "huge,"" the way personal computers split the market with mainframes. "The revolution is truly upon us and we have not yet begun to understand the implications on ground systems, launch infrastructure and commercial activities enabled by the new technologies."[50]

Pat Patterson of satellite-builder SDL thinks any prediction of the future is almost sure to be wrong, except for the basic fact that the microsat sector of the market will keep expanding for the foreseeable future.[51] Jeff Foust of the Futron Corporation, who has done

smallsat market studies, agrees, noting the "unknown unknowns" in space markets make specific predictions more than 10 years out ineffective.[52] Martin Sweeting is certain the larger microsats will "take on increasing dominance on space missions as instrumentation and payloads become further miniaturized." He is wary about predicting the role of nanosatellites but thinks that the potential is there for constellations or swarms of such satellites will be deployed to allow sensing covering ever greater volumes of space.[53]

The ORS Director and AFSPC Chief Scientist agree we should expect many new applications for microsats if the launch problem is solved, comparable to the flood of apps which emerged from countless developers when the iPhone went on the market.

Dr. Beason suggested an Army unit could call up a large constellation of microsats to provide persistent surveillance of a battle area with half-meter resolution. The ability to launch microsats in large numbers would enable them to demonstrate existing and new applications and undermine the current military concern that there's not enough utility to invest in microsats.[54]

Dr. Wegner thinks we're were already on the threshold of being able to make high-fidelity radar images from a constellation of microsats, and the problem will eventually be solved for optics. One military application he sees possibly orbiting in the mid-term is a large constellation of microsats, crosslinked into a global grid for sharing text and images—the way, he notes, young people now entering the military are used to communicating, as opposed to voice circuits.[55]

Many of the things spacecraft do involve balancing power and aperture requirements, and microsats so far have some limitations on both. Dr. Wegner thinks it's realistic we'll see ever-larger thin-film solar arrays deploying from microsatellites, providing power increases from the tens of watts available today to levels approaching a kilowatt.[56]

While there is great enthusiasm for new microsats, what is possible is not always what gets funded. Operational microsats should not, and will not, be funded just for the sake of getting smaller, and the launch equation remains muddled.

Satellite size is a complex calculation, in which conservative design using space-proven components favors larger satellites. Launch costs are an uneven factor, but given that dedicated launchers of any size are costly, the general direction is toward making smallsats smaller. The budget for the satellite itself is another factor, as is the state of technology for the particular mission.

We will not, for a long time if ever, see microsats taking over the most lucrative market, commercial communications and broadcasting satellites, in the foreseeable future. (Such large satellites may develop into a market for SNAP-1-type "barnacle" support microsats, though.) Dr. Griffin advises smallsat makers to "stop apologizing for not being able to do everything" and press on in the many fields we know smallsats are good at.[57] Dr. Wegner offered similar advice: exploit all the possible niches while waiting for advancing technology to open up new ones, maybe even including supplanting large satellites at some point in the future.

One trend sure to continue is the addition of more nations to the "satellite club" through the use of microsats. By the end of 2012, a Spanish CubeSat will fly experimental systems for deploying antennas and solar panels along with a software-defined reconfigurable radio. Vietnam's F-1 will have a 3-axis spin-dependent tunneling magnetometer, Ecuador's NEE-1 Pegasus will test a carbon nanotube thermal control system, and the ESTCube-1, from the University of Tartu in Estonia, will test an electric solar wind sail (where there is no physical sail, but an electric field), a concept attracting considerable interest among microsat researchers since it was proposed in 2008 by Finland's Pekka Janhunen.[58] Additional nations will no doubt become spacefarers in another decade.

It bears repeating that the examples just mentioned will use satellites that can be held in a human hand and are built on buses costing only in the thousands of dollars. (NASA's 3U GeneSat, at $6M, may have been the costliest CubeSat-based mission, which indicates just how much technology can now be packed into a small space.)

We can expect to see more of both classes of developments as outlined by Dr. Panholzer. Consumer electronics and industrial applications will keep driving down the size of components, while new concepts will continue to emerge. Those already formed (fractionation, virtual apertures) will be space tested, while some not imagined today will surely emerge. The NRL's Wilhelm suggested another decade will see an array of improvements in applying micro- and nanotechnology, including miniature control moment gyros, magnetometers, cameras, and the use of memory alloys to make very precisely patterned deployable antennas.[59]

There will be continued improvements in the miniature instrumentation that can be fitted on a microsat to enable new science missions, with ExoplanetSat being a near-term example. A few years further out is the

Space-Time Asymmetry Research (STAR) project, which unites NASA Ames with two American universities and three foreign partners, involving students in developing a series of five 100-kg class microsats with highly advanced laser interferometers to look for space-time asymmetry violations and thus test key principles of physics.[60]

The Power of Numbers

One area sure to see intensive development is the technology behind improved constellations, cooperative satellites, and swarms. Sir Martin Sweeting suggests some of these may operate with other larger microsats in the "mother ship" role. Satellite designer Ivan Bekey calls the principle involved "replacing structure with information." Large numbers of satellites need to be positioned without using a booster to many different orbits/locations, but in addition to propulsion advances, there are a number of clever techniques in the deployment and maneuvering of clusters that can result in desired patterns, even complex ones, with minimal or no use of propellant.[61]

Another is chipsats. One intriguing thing studied about chipsats is their ability to use the forces permeating the solar system for formation-keeping and propulsion. A sufficiently small and light chipsat could act as its own solar sail, or with solar cells and two 1-m wires serving as capacitors could be nudged 400m a day along a semimajor axis by tapping the Lorentz force provided by Earth's magnetic field. Sweeting foresees swarms of such chipsats adapting to the conditions the way a biological entity would.[62]

We have just begun, though, to see what microspacecraft can do in constellations or as secondary payloads. Truly large numbers require new manufacturing techniques: the largely hand-built satellites of today don't lend themselves to mass production. However, advances in production are significant and will play a much bigger role in the future.

Aerospace's Dr. Helvajian proposes adapting a number of current and emerging techniques, including modularity with functional modules plugged in via an increasingly popular standard called SpaceWire, 3-D layering fabrication, development of customizable multifunctional modules (MFMs), and the use of materials like photosensitive glass ceramics as a substrate for electronics.[63] Dr. Panholzer expects we may eventually see manufacturing in space that includes satellites being rolled out "like paper towels," with ever more complex electronics embedded in structural materials.[64]

Microspacecraft Beyond Earth

More deep space exploration using microspacecraft is almost certain, although the shape it takes, and how much is funded, is to be determined. While a cost of $1M to send a kilogram to Mars would appear to drive managers to smaller payloads, there's no small Mars launcher: if an agency must buy a medium-class booster to get to Mars, it will encourage spacecraft designers to use all the payload capability that has been paid for. Constellations/swarms which can use all the available capacity (as primary or secondary payloads) while delivering major science payoffs may profit from this calculus.

As the state of technology advances, the ability of microspacecraft to ring a target planet for communications or planetary science will be exploited the way it is around Earth, and small spacecraft are the only way to land in many places at once. The technology for micro-rovers is advancing as 29 teams in the U.S. and elsewhere are building entries for the $30M Google Lunar X PRIZE.[65] Team Italia, for instance, combines the resources of Italian universities and aerospace companies in a plan to a swarm of tiny "spider-bots," using both legs as well as wheels to explore the terrain. The Google sponsorship also highlights the potential of microspacecraft to find funding sources other than governments, something already happening on a large scale with CubeSats.

Dr. Griffin believes microspacecraft will "hit their home run" in future exploration, when human exploration beyond LEO creates a need for navigation and communications systems with nodes at the Moon, Mars, Lagrange points, and asteroids as well as in solar orbits.[66] Dr. Worden of NASA Ames, when an Air Force general, suggested sending more microspacecraft to Near Earth Objects (NEOs) to collect information needed to deflect an asteroid that might collide with the Earth.[67] This raises the thought of keeping quick-reaction "scout" microspacecraft ready to investigate newly discovered threats.

In Earth and in space, missions like the successful THEMIS and the upcoming ExoplanetSat will likely beget new missions using the ability of microspacecraft to observe from many points. A proposal from DARPA's Dr. David Barnhart to use 10-100 microsats to study ionospheric "plasma bubbles" that disrupt radio communications is an example of this principle.

CONCLUSION

Microsat technology has advanced enormously over five decades, and it may be that the explosive growth of the last two decades will continue, if not accelerate. The hard physical limits of satellite and instrument size exist, but engineers are already doing what was thought impossible at the turn of the millennium. Three trends in particular we see continuing or accelerating are increasingly capable constellations/swarms, the use of microsats in missions beyond Earth, and the addition of more organizations and nations to the microsat community. (The missions listed in the paper are only a small selection of planned microsats to illustrate the amazing diversity of organizations and applications in a world microsat community expanding like a supernova.) These trends and others may deliver greatly expanded use of microsats in the coming decades.

Much depends on how (and to what extent) the launch problem is solved: the futures with and without an MLV may look very different. Technology will have some impact on how different: for space science and some other applications, the mission works if a small launcher or secondary container can disgorge tens or dozens of very sophisticated spacecraft that can cover orbits or planets in a coordinated network with increasing degrees of autonomy and intelligence. It's very difficult not to be bullish about the continued development of microspace in a world where the desire to explore and exploit space is seemingly endless, despite the launch question.

The smallsat community has always had a praiseworthy sense of collaboration, producing an environment in which ideas are shared without undue regard for divisions between companies, agencies, and nations. Combined with the proliferation in space participants (some 50 nations now have space agencies), space technology projects, and the need for budget discipline, this creates a fertile ground for further advances. The challenge for all those in the smallsat industry is to continue the collaboration while advancing the state of technology and making a strong case for smallsats – not overpromising, but making sure decision-makers in space-related fields and agencies understand what can be done with modern microspacecraft.

If this challenge is picked up with enthusiasm, the 50th Conference on Small Satellites is likely to be a very interesting event. There will be reports on probes examining planets, asteroids, and comets, mission results that showcased the adaptation of microsat swarms and constellations to all kinds of challenges, and examples of breakthroughs in propulsion, intelligence, and other microsat capabilities. The 50th Conference will be an interactive forum with participants around the globe, in orbit, and perhaps on the Moon and other celestial bodies, discussing and connected by microspacecraft which today may not even exist even in the minds of the farthest-sighted scientists and engineers.

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