Cubesats: A Technology and Science Mission Low-cost Test Bed

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Abstract. With the demonstration of low cost pico-satellites, and the development of Stanford University's Cubesat program, a new test bed for technology and science demonstrations is gaining acceptance. Cubesat spacecraft, having a mass of approximately 1 kg, are appropriately suited for test and qualification of microelectronics and MEMS technologies. While these spacecraft currently have subsystems with limited functionality, existing micro-fabricated technology and new technology under development for space will quickly change this picture. Examples of capabilities and technologies on the micro-system level achievable in the next few years are ion thrusters, precise attitude control, formation flying, dynamic mesh network communications, and micro-scale plasma and environment sensors. Examples are discussed where SRI and Stanford are working to demonstrate technologies on Cubesats while also providing students with exposure to the full scope of systems engineering that is typical with more traditional spacecraft projects. Furthermore, scientific studies involving constellations and multi-point measurements can be carried out at costs previously considered unrealistic. With the cost and operational expenses of a Cubesat type system within research level budgets, organizations such as SRI and Stanford are taking advantage of rapid space technology prototyping to challenge traditional aerospace system development assumptions.

Introduction

In recent years the trend to smaller and lower power electronics has made it possible to fly pico-satellites, or picosats, with mass less than 1 kg and able to accomplish useful missions. In early 2000, Stanford University demonstrated the launch and operation of picosats deployed from a Stanford build micro-satellite [1]. Over the last few years, the continuing decline in the size and power of commercially available electronics and sensor systems means that picosats today can have computing capability comparable to micro-satellites of only a decade ago and are able to carry out scientific missions not thought possible just a decade ago with this size spacecraft. As a result, mission possibilities continue to evolve for picosats.

Due to the limited surface area and volume of a picosat, the available power from batteries and solar cells was a major limiting factor in the first Stanford picosats. As a result, Stanford's Space Systems Development Lab (SSDL; web site at http://ssdl.stanford.edu/aa/) under the direction of Prof. Robert Twiggs put forth a new design concept called a "Cubesat" to help in standardizing opportunities for picosats and to make more power available than in the first picosats. These Cubesats are providing a low cost space access opportunity to many universities and research groups, with launch opportunities planned for at least once per year [2].   The first mission involving some 14 Cubesats is expected to launch in early 2002, with satellite sub-systems, launch and support services being provided by One Stop Satellite Solutions, Inc. (http://www.osss.com). An example Cubesat rendering is shown in Figure 1.
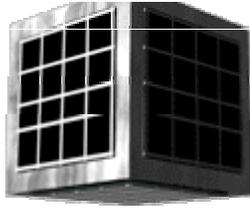
Figure 1. Rendering of an example Cubesat satellite, a 10 cm on a side cube.

As a result of the low cost space test opportunity represented by Cubesats, SRI International is one of many organizations collaborating with Stanford on the use of Cubesats to test new technology and mission concepts. In the discussion that follows, some of the technologies and missions concepts SRI is considering for Cubesat testing are discussed. In each of these cases, Cubesats will provide a significant test capability and will allow for rapid development cycles for a technology or mission concept that would normally take many years to develop and fly.

Cubesat Technology Development

One of the most promising uses of Cubesats is as a technology testbed for new small-scale space technologies, e.g. micro-electro-mechanical systems (MEMS). But, not only can Cubesats provide a testbed capability for low power, low mass devices such as MEMS sensors or components, but with the decreased cost, power, and size of communications equipment, compute power, and electronics, these MEMS and related small scale systems can be used to conduct useful science and missions. Example missions that are particularly relevant, because of the low cost of each Cubesat, are constellation missions involving multi-point and coincident measurement of ionospheric or environmental parameters. NASA has already defined a Magnetic Constellation mission concept, called MagCon, which is intended to fly a constellation of 50 to 100 nano-satellites (in the 10 kg mass range) to study the vector fields and flows of the Earth's magnetosphere (web page reference at http://stp.gsfc.nasa.gov/missions/mc/magcon.htm). At the current pace of technology development, Cubesats combined with new sensor, communications, and networking capabilities, may be able to carry out the MagCon mission concept before the anticipated launch date of the MagCon mission itself (sometime in 2007).

Technologies that have already reached a level of miniaturization suitable for Cubesat use include technology for almost every subsystem on a typical satellite. Power systems, thermal systems, attitude sensors, communication systems, and even command and control systems exist commercially with low enough power and mass to be incorporated into typical Cubesats (although usually with a need for repackaging and interface changes). As an example of how this can be true, the current cellular phone-personal digital assistants and wearable computers that many people regularly carry combined with solar cells and a few MEMS-type attitude sensors would essentially be a picosat if launched into orbit. Combined with new wireless communications protocols and standards being incorporated into wireless chipsets, such a picosat would even be capable of dynamic mesh network communications between members of a constellation using commercially off-the-shelf technology. Consequently, the biggest challenge for future picosat and Cubesat designers may very well be integration and packaging of a growing collection of commercially available technologies to accomplish the desired mission goals.

However, some satellite subsystem technology areas are noticeably lacking in capability at present. In particular, power capabilities of even Cubesats are very limited and propulsion capabilities of picosats are in general primitive. Existing Cubesat designs do not have active orbit control capability and are typically not attitude controlled or are limited to gravity gradient stabilization, magnetic torque systems, or simple spin systems for attitude control. Significant enhancement of mission capabilities would be realized by the development of micro-thrusters that would allow a greater degree of orbit and active attitude control for Cubesats. In addition,

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work on MEMS-scale attitude control actuators will provide added capability. Similarly, technologies that would provide higher power levels to Cubesats would dramatically increase the operational capabilities and communications power available to Cubesats. Existing Cubesats are expected to be capable of providing on the order of 100 milli-watts of continuous power from solar cells, or significantly larger power for short periods of time from batteries or storage systems.

Technologies in these two areas that SRI has been interested in, that may exist within the next few years, and that could be tested on orbit within a similar timeframe include micro-thrusters sized to the power, mass, volume, and thrust requirements of Cubesats, and miniaturized electrodynamic tether systems that would enable high power operation for Cubesats. The value of micro-thrusters is readily apparent, since it would provide the ability to duplicate attitude control capability currently found in larger satellites; but the use of tethers for power generation has a number of less obvious features.

Electrodynamic tethers can provide useful power, but do so at the expense of converting orbital energy to electrical energy – i.e. decreasing orbit altitude. This may be a highly desirable feature given that concerns are already being raised about the orbital lifetimes of proposed Cubesats. Hence tethers may not only provide short-term high power operation for Cubesats, but they may also provide a natural mechanism for rapidly de-orbiting Cubesats. Orbit lifetimes of thousands of years can be readily decreased to weeks or months by consuming power at rates of 1 to 10 watts in a small tether system (what one might call a "micro"-tether). Such power levels would, for example, significantly augment the communications and sensor capability of Cubesats.

Another interesting aspect of electrodynamic tethers is the ability to reverse the direction of current flow (if adequate power is available), and provide orbit-raising thrust. While this author has not verified in what altitude regime a Cubesat system could overcome other forces, such as drag, to accomplish orbit raising using solar cell generated power, an orbit raising and control demonstration could clearly be carried out with a Cubesat over a short period of time using stored or battery power. Orbit raising with a Cubesat and electrodynamic tether opens up interesting mission possibilities, especially since it represents a propellant-less propulsion mechanism that could provide new orbit modification capability to Cubesats without the limited lifetime issues associated with thruster technologies. However, the most useful application for tethers and Cubesats may still be those of high power short duration mission capability or related tether concepts such as use of conducting tethers for electric field monitoring or for formation flying using non-conducting tethers. The creativity of mission planners and the needs of future missions will determine the probability of these techniques being used.

SRI Technology Development

Technologies that SRI has developed or is developing that are suitably scaled for picosat missions include highly efficient field emission devices and ionization sources. In the sections that follow, background is provided for each of these technologies, and some implications of new capabilities these enable are discussed.

Field emission microfabricated devices have been used successfully over the last several decades in many high vacuum applications, including mass spectrometry, flat panel displays, and microwave tubes. They have found use primarily where clean, low power, and cold devices are needed to provide electrons or ions. For example, grouped in arrays from a single tip to millions of tips per square centimeter, a field emission array cathode is a device capable of emitting controlled electron currents from a low power, cold cathode with current densities of over to 5000 Amps/ cm^2. Recent interest in highly efficient electron and ion sources for space applications, especially electric propulsion, has resulted in a new look at these lightweight microfabricated devices.

SRI International has been involved in research into the design of vacuum microelectronics for many decades. Early studies of field emission by Charles Spindt

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at SRI resulted in the development in the late 1960s of the Spindt cathode [3] and in numerous patents on this technology during the 1970s and more recently. Most of the effort in the early decades involved fabrication techniques for single tip cathodes and small arrays. Since that time, SRI and Spindt (who remains active in vacuum microelectronics research at SRI) have made many improvements in the basic cathode structure and the robustness of arrays of cathode tips. The results of this research and development have been superior device characteristics in areas such as emitter tip density, emitter tip current capacity, and device lifetime. For example, lifetime tests have shown continuous operational life of up to eight years, with the test being terminated because of equipment failure, not a cathode failure. The references Spindt et al. [4] and Brodie and Schwoebel [5] are recommended for detailed background on emitter array capabilities and technology development across the gamut of field emission applications throughout the 1980s and 1990s both at SRI and at other research laboratories.

The low power and light weight of field emission devices make them ideally suited to space applications requiring electron or ion sources, while the efficiency and emission characteristics of the devices provide the ability to emit currents over many orders of magnitude, limited only by thermal considerations, and space charge effects. Furthermore, field emission electron sources of the Spindt cathodes type have been operated over temperature ranges from 4 degree Kelvin to 1100 degrees Kelvin, a range covering that of most space applications. Applications that have been considered include spacecraft charge control, electrodynamic tether propulsion, ion and plasma propulsion, and electron beam emission. The development of even more robust electron emitter arrays remains an active area of research driven primarily by applications in the areas of flat panel displays and rapid turn-on, high current electron sources. Figure 2 shows electron micrographs of example Spindt cathode tips and a section of one type of cathode array.

Basic SRI Spindt cathode emitter arrays consist of an insulating layer sandwiched between two conductors, with an array of holes in the top conducting film and in the insulating layer. The top conductor is referred to as the *gate*, and the lower conductor as the *base*. The arrays can be manufactured on any flat, smooth, ultra-vacuum-compatible substrate, either insulating or conductive (see schematic in Figure 3). The emitter tips are fabricated in the array of holes using thin film deposition techniques and have been fabricated with sub-micron hole spacing, or packing densities of over 5×10^7 tips/cm^2. For such a cathode structure, adjusting the voltage of the gate layer relative to the emitter tips controls the emission level. Because of the small scales involved, only small voltages (typically less than 100 volts) are required to control emission from each tip. Per-tip electron emitting capacities of well over 100 microamps have been demonstrated with single tips, resulting in a theoretical emitted current density of 5000 amps/cm^2 for arrays with packing densities at the levels that have been demonstrated.
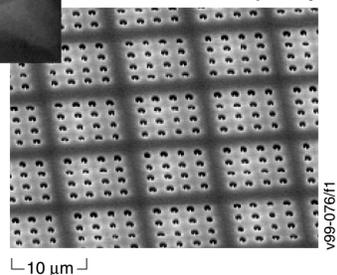
a. Close-up of single tip
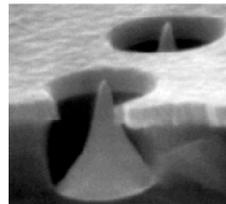
b. Portion of 10,000-tip array

├─ 1 µm ─┤

├─ 10 µm ─┤

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Figure 2. (a) Electron micrograph close-up of Spindt cathode tips, and (b) close-up of a section of a cathode array.

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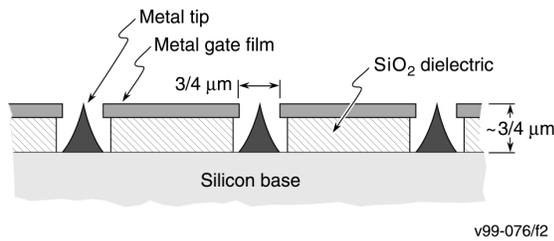
v99-076/f2

Figure 3. Schematic of a Spindt cathode array.

With such high current densities and the inherent small size and small mass of microfabricated devices, Spindt cathodes have excellent characteristics for space applications. Nonetheless, to have an advantage over existing technologies with regard to space applications, a number of additional characteristics are highly desirable. These include not only low mass and small size, but also low power consumption, clean operation, no use of expendables, high efficiency, long lifetime, and a large operational temperature range. Spindt cathodes clearly have small size and low mass by nature of their microfabricated structure, and tests have shown that they can exhibit very long operational lifetimes. The true value of Spindt cathodes as electron emitters in space is further demonstrated by the fact that these devices do indeed have extremely low power requirements, extremely efficient operation, extremely clean operation, and require no expendables. Furthermore, demonstrated ability to operate over temperature ranges from 4 degree Kelvin to 1100 degrees Kelvin makes Spindt cathodes well suited to space applications.

To explore the efficiency and electron emission capabilities of Spindt cathodes one can use the accepted model for field emission occurring in a Spindt cathode, the Fowler/Nordheim equation, which has the form

$$I = (n\,a)\,V^2\,\exp(-b/V). \qquad (1)$$

The variable n represents the number of emitter tips in the array. The coefficient a is related to the effective emitting area per tip and the tip geometry, where the total effective emitting area depends on the

atomic-scale details of the emitter tip surface as well as the number of tips in an array. The coefficient b is proportional to the 3/2 power of the emitter work function. (See previously mentioned references for further detail.)

Rearranging the above equation and taking the log of the result produces

$$ln(I/V^2) = ln(n\,a) - (b/V). \qquad (2)$$

A Fowler/Nordheim plot is a graph of $ln(I/V^2)$ vs. $(1/V)$, which, for true field emission, produces a straight line with a slope of b and a y-intercept of $ln(n\,a)$. Thus, experimentally obtained data from an emitter array having a known number of emitter tips can be used to determine the a and b coefficients for this type of cathode, and these coefficients can then be used to predict the performance of similar emitter arrays or to design emitter arrays to meet given sets of specifications. The experience with such emitter arrays at SRI has been that 1 microamp per tip is a very comfortable level of emission for these cathodes, and emission levels of over 100 microamps have been obtained from single emitter tips.

As an example of typical values, from the Fowler/Nordheim plot of a sample 1024-tip array, values of $a = 9.72 \times 10^{-7}$ A/V^2 per tip and $b = 717$ V were obtained. From such a result, the experimental data can be extrapolated to larger arrays and emission levels for purposes of considering the emission capabilities of a large Spindt cathode device in space. Figure 4 shows just such a plot of modeled emitted current versus applied control voltage for a 5-million-tip array, which could be readily manufactured with existing techniques. From the plot we see that a 0.01 amp emission current would be achieved with approximately 70 volts applied between the base and gate electrodes, and that a healthy 0.1 amp current would be emitted by such a 5-million-tip array with an increase in the gate voltage of only 15 volts, to approximately 85 volts. This plot highlights a very significant characteristic of Spindt cathode emitters, the value of SRI's integrated gate structure, which allows low voltages between the gate electrode and tips to control the emission of electrons.

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To emit large currents in space, the emitting source might require a large negative bias or large accelerating voltages, but these need not be part of the control voltages (or power drain) associated with operating the devices. In fact, in cases where the emitting spacecraft has a large negative bias and where minimal power consumption is desired, the devices can be operated in a "self-powered" mode. To achieve this self-powered mode the naturally occurring spacecraft-to-plasma potential difference is used to drive the electron extraction and acceleration, at least until the spacecraft frame potential reaches the threshold voltage needed for field emission to take place. This self-powered mode has been proposed for use in spacecraft charge control or for missions that naturally have large potentials between spacecraft components (e.g., electrodynamic tethered satellite systems)[6]. With the features of low voltage and power drain, and a possible self-powered mode, Spindt cathodes have clear advantages over traditional electron emission technologies when applied in space.
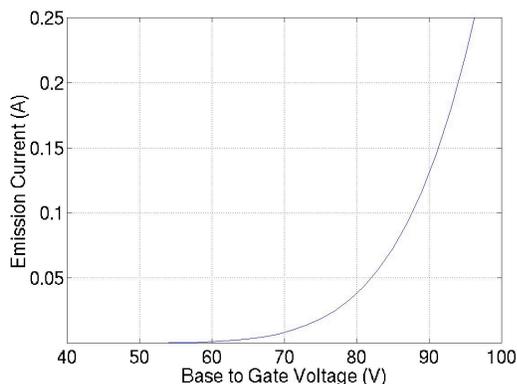

Figure 4. Modeled values of emitted current vs. gate voltage for 5-million-tip Spindt cathode.

To consider the value of Spindt-cathode-based electron emitters in space, it is also useful to compare this technology with two other technologies typically applied to produce electron currents in space. The examples considered here are thermionic emission (by far the most commonly used)

and plasma contactors (ionized gas cloud devices typically used for large currents). With regard to thermionic emitters, such as are found in typical electron guns, Spindt cathodes are extremely efficient, have much lower mass, and avoid most of the contamination and outgassing associated with hot cathodes. With regard to plasma contactors, not only are Spindt cathodes much more efficient and lower mass, but they do not require a hot cathode, they can respond very quickly (in the microwave frequency regime), and they have a smoothly varying output over their full operating range. More important, however, Spindt cathodes require no expendables, a major system design issue associated with plasma contactors.

Ion sources based on similar microfabrication techniques have also been produced for several applications and are discussed in the references already mentioned. These devices rely on a phenomenon known as field ionization, where similar to field emission, high electric fields result in ionization of target molecules, with electrons tunneling to the electrode structure and the ions escaping as a result of the field direction. These field ionization devices require an expendable material or propellant that is ionized, and the devices can operate with both gas and liquid phase expendables. When operated with liquid metals, these are microfabricated versions of liquid metal ion sources, and can be highly efficient producers of ions and have extremely low mass. Figure 5 shows an electron micrograph of an array of such field ionization elements developed for a mass spectroscopy application. Structures similar to this can be adapted for use with liquid metals. Operated in arrays of this type, the high ionization efficiency achievable results in very low power, low mass, and low burden ion sources suitable for many applications.

Space Applications of Field Emission and Ionization Sources

The many advantages of Spindt cathodes as electron sources result in a variety of possible space applications. While Spindt cathodes can literally find use anywhere

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electrons are needed, it makes the most sense to focus on applications where their low mass, low power, small size, and high efficiency are the greatest assets. Examples of such applications are electric propulsion, charge control, sample ionization, electrodynamic tethers, and electron beam generation. In each of these applications, Spindt cathodes can provide significant improvements over existing technologies, although only one has been used in space to date. That example is the use of Spindt cathodes for electron impact ionization of mass spectrometer samples [7].
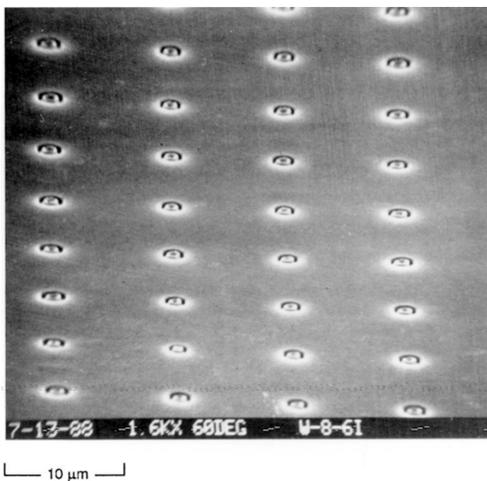

└─ 10 μm ─┘

Figure 5. Electron micrograph of one type of field ionization array.

The term *electric propulsion* covers many propulsion concepts, and Spindt cathodes can play a role in most. An example application that is being explored experimentally is the use of SRI's Spindt cathodes as ionizers for plasma propulsion systems. They have been used for sample ionization in terrestrial chemical analysis for many years because they are free of outgassing and hot cathode contaminants. Another natural application is in the area of neutralization of plasma and ion thruster plumes, where the mass, size and efficiency are highly desirable. SRI's Spindt cathodes are also being actively investigated for use in this propulsion charge neutralization application.

Similarly, field ionization ion sources such, as those developed at SRI have been suggested as an ion source for use in advanced ion engines. With SRI-type devices grouped in arrays of millions per square centimeter, the devices would provide highly efficient liquid metal ion engines with significant efficiency improvements over existing ion engines. The deployment of small satellites in particular has resulted in the need for such new propulsion systems for station keeping and attitude control functions that are extremely small and highly efficient. Electric thrusters, due to their very high specific impulse, can outperform conventional liquid, gas, or solid chemical propellant systems in these functions. However, existing electric propulsion approaches based on plasma ion sources are less than 50% efficient at converting electrical energy to thrust and require a moderate size and mass to operate, regardless of thrust level. On small satellites, where size, weight, and power are all at a premium, thrusters based on field ionization technology may provide a solution.

Such proposed thrusters could be designed to exhibit minimal grid wear, have thrust vectoring capability, conform to available real estate on the spacecraft, and to use direct current operation that will produce little or no electromagnetic interference (EMI). The two-dimensional layout of the thruster's physical design would allow its maximum thrust to vary in proportion to its exhaust area; therefore, its size could be scaled to accommodate a broad range of spacecraft thrust requirements or onboard power limitations. These combined characteristics should yield a very compact, long lifetime, multi-mission compatible thruster capable of both high-thrust, reduced-specific impulse maneuvers and low-thrust, high specific impulse station keeping operations. SRI is currently engaged in development of such a versatile, high performance thruster.

Electrodynamic tethers are essentially another form of electric propulsion, but are classically grouped in a separate category because of the large physical extent of typical tether systems relative to the small size of many electric propulsion devices.

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However, applications involving current flow in electrodynamic tether systems such as the one depicted schematically in Figure 6 would also benefit greatly from efficient, low-power, low mass electron sources such as Spindt cathodes, especially for application on picosats. These systems consist of a conducting tether that may be connected to end-bodies, and for which the motion of the tether through a magnetic field results in an EMF across the tether. This EMF can be used to drive a current through the wire if an electrical connection to the surrounding plasma is allowed—for example, at the endpoints of the system or along lengths of bare tether. In such a mode of operation, the resulting electrodynamic drag can be used to reduce the orbit of the system or to fully de-orbit the system. Similarly, if a power source is available and current can be driven through the tether in the opposite direction to that which would result from the motion-induced EMF, the interaction of the tether current with the ambient magnetic field can be used to raise the orbit of the system. (See [Banks, 1989] for further details[8].)

In this manner, electrodynamic tethers can be used for orbit adjusts, transfers, and de-orbiting and can be made to operate without the use of propellants. The efficiency of this process is significantly improved if the tether current can be maximized, and if the potential drop at either (or both) endpoints can be reduced. Spindt cathodes can help with both of these issues by providing very efficient electron emission and by requiring very little potential drop across the emitting device. Similarly, field ionization ion sources can be used for reducing power requirements associated with current closure to the plasma at the electron collecting end of a tether system, further improving the efficiency of an electrodynamic tether or removing requirements for large current collecting areas. Satellite de-orbiting is already being aggressively pursued for commercial application by Tethers Unlimited, Inc., a company with a long-life multi-stranded conducting tether ideal for this type of application.

In the arena of charge control, the idea of using field emission in space is not new [6]. The most natural
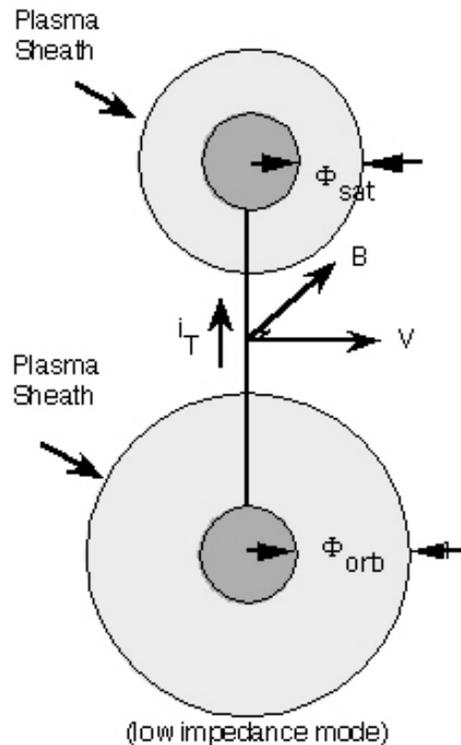

Figure 6. Schematic of an electrodynamic tether system flowing current.

application of electron field emitters is the control of spacecraft negative charging, found both in low Earth orbit (LEO) and geosynchronous orbit (GEO) environments. Negative charging is particularly prevalent because of the high mobility of electrons, and is readily controlled because there is no need for expendables as electrons are the only products to be emitted. Spindt cathode technology can also be applied to positive charge control, especially if materials are available for electron impact ionization. Similarly, if expendables are available, field ionization ion sources can be used to directly produce ions with very high efficiency. The application of these technologies to spacecraft charge control is also closely related to the application of Spindt cathodes as electron sources for electron beam generation, where the efficient field emission of electrons from small, low-power sources is beneficial. In the case of electron beams, Spindt cathodes have been substituted for thermionic emission as a source of electrons

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because they avoid the problems of hot cathodes, allow very rapid switching and control, and are capable of very high currents even with the use of small control voltages.

The characteristics of charging in the GEO regime make the application of Spindt cathodes to spacecraft charge control particularly appropriate. However in many application areas of picosats, natural charging should not be a significant problem; but if active operations induce charging, microfabricated field emission cathodes such as Spindt-type cathodes, are the only currently available low-power, small mass solution that would work within the power budget of picosats for active control of spacecraft potential.

Mission Concepts and Applications Issues

In addition to the kinds of technologies discussed above, other advances in sensors and communications technologies lend themselves to application on picosats. These include miniaturized sensors such as particle spectrometers, magnetometers, IR sensors, and optical or photodiode based sensors, many of which exist or are now being developed as MEMS devices. Some examples that are not MEMS-level devices, but are suited for the picosat scale application include the development of a Miniature Electrostatic Analyzer (MESA) by the Air Force Academy's Small Satellite Research Center and A Low Energy Particle Imaging Spectrometer (LEPIS) being developed by Physical Sciences, Inc.

Example missions that might be flown with such sensors and combinations of sensors include scientific and technology missions, such as NASA's MagCon mission. Similarly, lower altitude ionospheric monitoring becomes possible, especially with constellations of picosats, measuring particles, electric and magnetic fields, and atmospheric optical emissions. Technology demonstrations that might be conducted using picosats include optical network implementations and dynamic mesh network communications amongst satellites, where the term dynamic mesh refers to the situation where different satellites drop in and out of communications with each other

dynamically. Hence, picosats may prove to be a low-cost, rapid development platform for many of these new technology and mission concepts.

While picosats such as the Stanford proposed Cubesat holds great potential, there remain significant engineering challenges, especially involving small-scale sensors. Amongst these are materials issues such as exposure to atomic oxygen, particulate contamination, packaging, and handling. But even in these areas, the low-cost, rapid turn around possible with picosats should prove advantageous to the development process.

For example, while SRI field emission cathodes have been manufactured for differing applications out of many different materials, most research cathode designs were not explicitly intended for space applications, and hence one could further explore optimal designs and material choices to improve applicability to specific harsh spacecraft applications. For example, standard off-the-shelf research cathodes are made of molybdenum, which is expected to be susceptible to degradation at LEO atomic oxygen levels. In addition, cathode geometry changes have been proposed to address protection against particulate debris expected at LEO altitudes. For GEO applications, exposure to atomic oxygen can be avoided by use of enclosures while at low altitudes, protective coatings can reliably be used to chemically protect surfaces, and particulate debris is less of a problem. However, testing and design changes are recommended for LEO applications that would experience a constant exposure to atomic oxygen and exposure to particulates.

In addition, as with any microfabricated device, packaging and care of devices such as microfabricated cathodes and ion sources before they are put into operation is critical. These devices must be kept clean and free of contaminants before use and ideally exposed to the contaminants in a spacecraft environment only after significant spacecraft outgassing has occurred. This is an issue already addressed and resolved for space applications of other technologies, such as optical systems, but packaging remains an engineering challenge to be addressed for all picosat missions. Other system-level

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questions that may require attention for specific applications include power-on procedures that improve robustness and reliability by minimizing problems caused by contaminants or particulates.

In the specific case of field emission and field ionization devices various communities interested in applying field emission and field ionization to space application are actively addressing these challenges and flight opportunities are expected to become available in the near future. The flight test opportunities for these devices are made easier by the small size and very high efficiency. Even very small satellites, such as Cubesats, can be used to demonstrate and space test field emission devices. As a result, besides government and industry groups with an interest in flying cathodes, numerous university groups including Stanford University, University of Michigan, and University of Texas, Austin are considering Cubesat research missions involving SRI field emission cathodes. It is our intent to support these and other missions as test beds for development of field emission electron and field ionization ion sources specifically tailored for space use.

Summary

We have found that Cubesat-type picosats provide an excellent space test bed for component checkout and demonstration, testing of communications technologies, ionospheric research, and constellation and multi-point scientific studies. In addition, specific SRI technologies such as field emission cathodes can provide new and significant mission capabilities to picosats. The low power, low mass, and electrical characteristics of Spindt cathode field emission arrays provide a far superior alternative to existing approaches for electron emission or gas ionization in many space applications. Similarly, field ionization devices show promise as superior alternatives to traditional ion sources, and provide the potential for attitude and orbit control systems that can be integrated and tested on the scale size of picosats. As a result, SRI is taking an active role in testing and developing operational procedures,

packaging, and control systems for use of these devices on commercial and scientific picosats. In particular, in the areas of electric propulsion and spacecraft charge control, these devices could provide a set of technologies and capabilities previously not available to the smallest class of spacecraft.

The capabilities and mission options for picosats will continue to evolve rapidly as the low-cost access to space afforded by picosats is more widely recognized as an engineering asset. Nonetheless, the biggest challenge for future picosat and Cubesat designers may very well continue to be integration and packaging of a growing collection of commercially available technologies to accomplish the desired mission goals. Overcoming this packaging and integration challenge will open up space test options to a much broader community than has been previously possible.

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