Microspacecraft And The Vision For Space Exploration

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ABSTRACT. In 2004, President George W. Bush gave the National Aeronautics and Space Administration (NASA) a new focus: the Vision for Space Exploration (VSE). The VSE, which includes a human presence on both the Moon and Mars, requires a space infrastructure which will more closely resemble a polar expedition (with its system of base camps, supply depots, etc.) than previous space programs. In this effort, the roles of scouts, communication nodes, and rescue parties may well be played by a network of microspacecraft spanning the vastness of the Earth-Moon-Mars system. The need to put unprecedented capabilities in space at manageable cost makes it important to examine the smallest, lightest, and most affordable machines which may be suited for each required task.

Microspacecraft technology, much of it already demonstrated (e.g., NASA's AERcam Sprint and the Air Force's XSS-10) or in flight testing (e.g., NASA's SPHERES and Space Technology 5 (ST5) missions), can help reduce costs and maximize crew safety. Possible roles for microspacecraft include inspecting larger vehicles for damage, assisting astronauts on extra-vehicular activity (EVA), in-flight servicing, scouting out conditions on other celestial bodies, and providing communications services, sensing, and navigation from lunar and Martian orbit.

The overall concept arising from our preliminary study of these roles is a network of small spacecraft providing a variety of support to the large robotic and human-carrying craft required by the VSE. In a practical VSE architecture, microspacecraft are likely to play a much larger role than their size – or current thinking – would suggest.

INTRODUCTION

The U.S. civilian space effort, outlined by President George W. Bush in the January 2004 Vision for Space Exploration (VSE), foresees placing permanent bases on the Earth's Moon and, eventually, Mars. The National Aeronautics and Space Administration (NASA) is still developing the details of this grand campaign. Project Constellation, the effort to develop the needed technology for human exploration, is only part of an infrastructure-building program more akin to the scientific exploration of Antarctica than to existing space programs.

NASA's Exploration Systems Mission Directorate (ESMD) has an exciting but daunting task ahead of it. Already, NASA's budget increases have fallen short of those projected in 2004. One effect of this has been that the two main components of the VSE launch hardware – the Crew Launch Vehicle and the Cargo Launch Vehicle – were forced to undergo redesigns to save money, at a cost in performance. Another effect

was apparent in the 2007 budget submission, where NASA chopped its five-year Mars exploration budget by half as part of a \$3.1B science cut.

The National Academies' Space Studies Board recently warned, "The agency does not have the necessary resources to carry out the tasks of completing the International Space Station (ISS), returning humans to the Moon, maintaining vigorous space and Earth science programs, microgravity life and physical sciences programs, and sustaining capabilities in aeronautical research."¹

NASA cannot shed any of these missions, and the agency is unlikely to get a major funding hike. To accomplish the VSE in this budgetary climate requires an innovative look at all the approaches and technologies that might contribute. One relevant technology is microspacecraft. In this paper, we survey the recent developments in microspacecraft and offer preliminary concepts for their employment as part of the VSE architecture.

The Microspacecraft Option

A program of exploration requires scouts, rescue parties, and other ancillaries to support its main parties and bases. In the VSE, many of these roles are well suited for microspacecraft. Every kilogram lofted to Earth orbit currently costs \$5,000 or more. Putting the same kilogram on Mars costs an estimated \$1 million(M). The need to provide unprecedented capabilities with minimal mass and manageable cost should drive planners to thoroughly examine the potential role of microspacecraft throughout the VSE.

There are several features of microspacecraft which warrant this kind of systematic utilization. First, microspacecraft normally have lower development costs, shorter development timelines, and lower launch and operations costs than larger spacecraft: all welcome features for a program which, as the President's Commission on Implementation of United States Space Exploration Policy, (a.k.a. the Aldridge Commission) stated, "will need to be managed within available resources using a 'go as you can pay' approach."² Such savings come with tradeoffs concerning capability and longevity, but that point leads to the second feature: not every task requires tradeoffs to employ microspacecraft. Microspacecraft are sometimes the most effective way to perform a mission, especially missions requiring in-space inspection or sensor measurements from multiple locations.

A third feature is that microspacecraft, including surprisingly sophisticated ones, are commonly developed by or with the help of universities. This facilitates the strong educational component NASA seeks to include in the VSE.³ Fourth. use of microspacecraft can facilitate participation by international partners which often lack the budgets to develop more ambitious missions. The use of microspacecraft as part of an exploration architecture also allows engineers to make maximum use of each launch vehicle, as microspacecraft can "fill in" any Finally, unused capacity. development of microspacecraft systems and components, which must minimize mass and power requirements, can pay dividends in reducing those requirements for larger spacecraft.

NASA is paying some attention to the uses of small spacecraft. Some individual programs inside and outside the VSE have considered "going small" in the course of their own option studies. There are also some cross-program technology development efforts, notably NASA's Mars Technology Program, which include work on shrinking spacecraft and components. Given that "microspace" is a rapidly developing field, though, the technological and operational advances in this area may not be familiar to engineers in some VSE programs. Others may incorrectly associate microspace in general with the controversial "Faster, Better, Cheaper" approach NASA tried in the 1990s, when in fact microspace has long since moved on and incorporated the lessons of that era.⁴

We are here suggesting that NASA should take the logical next step in microspacecraft: making maximum use of their utility across the VSE by having a single entity examine their applications holistically as part of ESMD's Exploration Systems Research & Technology effort.

For the purposes of this paper, we define microspacecraft as small, single- or dual-mission devices, usually under 100 kilograms (kg). The mass figure is arbitrary, but is commonly used in reference to microsatellites, and will serve to focus the discussion. This paper uses the general term "Pioneering Robotic Microspacecraft Scouts," or PRISMs,⁵ for VSE-enabling microspacecraft, whatever their task.

BACKGROUND

When President Bush proposed the VSE on January 14, 2004, he directed the Space Shuttle be phased out by 2010 and a new launch system developed. The practical effect of this is that the U.S. will return to the use of expendable launch vehicles (ELVs) to launch the Vision's crewed and robotic spacecraft.

The Aldridge Commission was impaneled to develop the basic approach to making the VSE practical. The specifically Commission did not mention microspacecraft, but did have some relevant technologies on its priority list, including lighterweight structures, miniaturized avionics, and formation flying technology.⁶ The November 2005 Exploration Systems Architecture Study (ESAS) report codified reliance on ELVs to get the program going more quickly and cheaply.⁷ The continued use of ELVs means no drastic launch cost reductions can be assumed in the near- to mid-term, and thus a continued emphasis on performing the mission with minimal payload mass requirements.

While the first U.S. spacecraft were microsatellites, the overall trend since the beginning of the Space Age has been toward increasing the mass of individual spacecraft. Larger spacecraft permit the lowest cost per unit capability (such as bandwidth on a communications satellite) and the carrying of multiple experiments, although at the price of higher total mission costs and longer development schedules.

In the last decade, technology, from microcircuitry to "folded optics," has increased the work that could be done from a small platform. In the U.S., sophisticated rendezvous and inspection satellites like the Air Force's XSS-10 and XSS-11 are important examples. The Air Force's upcoming STPSat-1 small satellite will eject two 1-kg "picosats" to demonstrate communications technology. In the commercial realm, communications microsats were employed for the successful Orbcomm VHF/UHF constellation of 34 42-kg satellites in low Earth orbit (LEO).

Microspace technology is advancing in other nations as well. One relevant example is the 5-kg SNAP-1 inspection microsatellite tested by a leading British firm, Surrey Satellite Technology Ltd. (SSTL).⁸

These advancements have led to a series of proposals to use microspacecraft in exploration roles outside Earth orbit.⁹ Some examples already been flown: NASA's ST-5 mission, consisting of three 25-kg science satellites, was launched in March 2006 to test new technology while studying the Earth's magnetic field.

REQUIREMENTS OF THE VSE

The VSE, like any other expedition intended to create a permanent presence on far-distant shores, is a longterm undertaking with massive logistical requirements. The ESAS report described NASA's preferred approach to the human spaceflight requirements of the VSE. This approach is only the first step toward a broader architecture, which will continually evolve as new knowledge and technology are factored in. This architecture will draw on modern network-centric concepts to ensure the needed robustness and flexibility.

The closest analogy to the VSE, involving first penetration and then colonization of a hostile environment, may be the Antarctic expeditions of Admiral Richard Byrd. His flight over the South Pole in 1929 was an Apollo-type sortie. In Operation Deep Freeze, conducted under his command in 1955-56, Byrd's men built up a network of base camps, scientific stations, and supply caches, connected by radio and aircraft, planting an infrastructure for human activity on the continent. Air and ground scouting parties were used to chart routes, map hazards, look for missing expedition members, and locate resources such as seal colonies. It was, in modern parlance, very much a network-centric operation.

Analogously, the VSE will employ a series of large spacecraft, both crewed and robotic, and eventually permanent base camps on other celestial bodies. These will be part of a network that includes communications and logistics nodes, robotic scouts, and information links using radio or laser communications. In this network, sufficiently capable PRISMs could fill roles including:

- 1. Inspecting the exterior of larger vehicles (crewed and uncrewed) for damage.
- 2. Assisting astronauts on EVA (fetching tools and equipment, recovering inadvertently released equipment, helping specialists assist the astronaut through telerobotics, etc.).
- 3. Servicing vehicles (transferring components, connecting propellant lines, etc.).
- 4. Providing communications services, sensing, and navigation signals from lunar and Martian orbit.
- 5. Landing on lunar and Martian surfaces to check the conditions of particular landing sites and probe for resources.
- 6. Fulfilling the Vision's call for a concurrent program of unmanned science spacecraft.

An expansive vision of the role of microspacecraft in the VSE would include craft being flung out ahead of the main expeditions into lunar and Martian orbit and perhaps points in between, while others touch down on the surfaces. In the next phase, each large vehicle might carry several microspacecraft, some mounted like barnacles on the hull, others kept inside to be released through airlocks as required. What we must examine is to what extent current and developing technology supports the possible use of microspacecraft in such roles.

The rest of this paper lays out the reasons for thinking that, while microspacecraft will not always be the best option for the tasks just described, recent technological advances definitely make them worth consideration The key question is, "In which cases can microspacecraft perform these VSE functions while saving money and mass?"

To reiterate a fundamental point: any answers to this question are not, at this early date, certainties. Tradeoffs for each mission area, such as large vs. small spacecraft or expendable vs. recoverable ones, will have to be examined individually in the context of the VSE architecture. While that architecture is still being fleshed out, an initial knowledge of what microspacecraft can do is essential to ensure the architects do not foreclose any promising options. This paper is written to lay out initial thoughts on those options.

TASKS FOR PRISM SPACECRAFT

Task 1: Inspection

Task 1 is the easiest to explore. Microspacecraft for the inspection and imaging of larger craft are a proven commodity.

There are two avenues of approach demonstrated so far. One, epitomized by the U.S. Air Force (USAF)'s XSS-10 and XSS-11, is for highly capable inspectors in the 25-100 kg class. Another, demonstrated in the 2000 mission of SNAP-1, is for very small, inexpensive, throwaway inspectors.

The 28-kg XSS-10, launched in January 2003, displayed the capability to locate, rendezvous with. and image a target (a spent upper stage) with a considerable degree of autonomy.¹⁰ The \$62M, 140kg XSS-11 followed in April 2005, undertaking a 12-18 month mission intended to autonomously find and image at least six targets in similar orbits from a distance of about 2.5 kilometers (km).¹¹ The SNAP-1, a coffee-can-sized satellite, detached from the mission carrying China's Tsingua-1 microsat and reacquired and closely inspected the larger craft. According to SSTL, "The SNAP-1 nanosatellite was a world-first in that it had 3-axis control, on-board machine vision payload, on-board GPS navigation and a tiny propulsion system that enabled it to demonstrate a rendezvous capability."12

In March 2006, AFRL awarded a contract to SpaceDev for design of the Autonomous NanoSatellite Guardian for Evaluating Local Space (ANGELS). The goal is to create a nanosatellite that would monitor the environment around a larger host satellite in geosynchronous orbit. The first flight is slated for 2009.¹³

NASA has tested an earlier technology, the AERCam Sprint, for this function. This soccer-ball-sized spacecraft, developed and built for \$3M, was successfully demonstrated on a flight in the opened Shuttle bay on STS-87 in 1997. Its subsequent shelving was debated after the 2003 *Columbia* disaster, since such a craft might have inspected the

Shuttle for launch debris damage.¹⁴ A "Mini AERCam" only 20cm in diameter has since been ground tested.

Given that the other method of examining spacecraft, sending out astronauts for EVA, is very costly, risky, and complex (and that most large VSE craft will not carry astronauts at all), it's highly likely this task will be carried out by PRISMs.



Figure 1. The 4.5-kg Mini AERCam (NASA)

In another relevant experiment, a resupply launch to the ISS in April 2006 carried the first prototype of the volleyball-sized Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES). Two more of these tiny craft, funded by NASA and DARPA, will go up later in 2006 for testing on the ISS. MIT's David Miller explains the next generation of SPHERES will operate in space, positioning themselves to an accuracy of one centimeter (cm) while performing tasks as EVA assistants, resupply, or repair craft. Advanced versions could also, via radio links, form linked constellations as part of huge telescopes or antennas.¹⁵



Figure 2. SPHERES Prototypes (MIT)

Task 2: EVA Assistant

When a task mandates that astronauts must go out on EVA, an accompanying PRISM could fill several useful roles. A PRISM could visualize areas difficult for astronauts to reach (for example, the far side of a beam the astronaut would have to reach around) and provide a view on a miniscreen in the astronaut's helmet. Equipped with a grappler, it could fetch additional tools and parts from the parent spacecraft as needed. It could also retrieve tools or parts inadvertently lost by the astronaut. SPHERES, SNAP-1, the AERCam programs, and potentially ANGELS could all be relevant technology sources.

Finally, a PRISM might be able to retrieve an astronaut whose safety tether became broken or detached. One way to do this would be for the PRISM to take a backup tether to the astronaut. The alternative of actually retrieving the astronaut by a PRISM requires a spacecraft somewhat larger than the AERCam, given the mass of an astronaut and the propellant needed to change one's inertia, but may still merit examination.

NASA has also examined the use of Personal Satellite Assistants (PSAs) inside large spacecraft, such as the ISS and the large-volume space habitats that will be needed for voyages to Mars.

Task 3. Servicing

The use of small spacecraft for servicing other craft has often been proposed, but little technology has been demonstrated in space. The first requirement for active servicing (transfer of fuel, changeout of modules, etc.) is the ability to hard-dock with the target spacecraft. Microspacecraft have been designed for this function under programs like AFRL's 1999 Advanced Satellite Technology (ASTEC) effort, which produced a 40-kg design with a one-kg transferable payload. This microspacecraft was estimated to cost only \$1.25M if produced in quantity.¹⁶

The first space demonstrations will likely be carried out by larger satellites. The U.S. DART mission failed in 2005, but the DARPA-funded two-satellite Orbital Express mission is slated for a late 2006 launch. While the two satellites involved are relatively large, one part of the rationale for the program is "servicing satellite can support deployment and operations of micro-satellites for missions such as space asset protection and sparse aperture formation flying, or deploy nanosatellites for inspection to provide data to support satellite repair."¹⁷

PRISMs could not handle all servicing missions, since some would require transferring large masses of fluids or equipment, but they offer promise for functions like changing out a circuit card or applying a tool to a stuck valve. The 1973 Skylab 2 mission, which required astronauts to perform an EVA to cut a metal strap keeping a solar panel from unfolding, is another example of the kind of task a microspacecraft could do in the future.

Task 4: Orbital Infrastructure

A full exploration of the Moon and the colonization of Mars requires a network of capabilities including communications, navigation, and remote sensing. One aim stated for NASA's Robotic Lunar Exploration Program (RLEP) (renamed the Lunar Precursor and Robotic Program or LPRP in May 2006) was to create a "Communication/ navigation structure" which "Ensures future missions don't have to bring their own."¹⁸ NASA Ames Research Center (ARC) Director Simon "Pete" Worden believes small, low-cost spacecraft are a promising approach to establishing these services, which he calls "lunar utilities."¹⁹ A related program in the VSE, based at Goddard Space Flight Center (GSFC) is the Exploration Communications and Navigation Project (ECANS). ECANS will develop the communications infrastructure supporting near-Earth and trans-lunar operations. ECANS engineers should take a particular interest in PRISM capabilities.

Such a capability was initially provided on Earth by microsatellites in the U.S. Transit navigation and DSCS-I communications satellite programs. Navigation and large-volume communications traffic have moved to larger spacecraft, primarily for costeffectiveness, and need to be reexamined to find the optimal approach for the Moon and Mars.

Comsat constellations around the Moon and Mars would be needed both to support exploration and to send science data back to Earth. Factors in the design of such constellations include the large amount of data that must be handled, and, in the Martian case, the greater power needed to transmit data in quantity to Earth. There are two basic options for this architecture. One is a network of microsatellites relaying through a larger geostationary craft; the other a smaller number of large spacecraft such as the now-canceled Mars Telecommunications Orbiter. The tradespace might be compared to that involved in computer networks, where central servers are being complemented or even replaced in new thin-client or distributed architectures. The comparison may be a literal one, as microspacecraft such as CHIPSat have used a TCP/IP protocol to become a node on Earth's Internet.²⁰

NASA's Jet Propulsion Laboratory (JPL) proposed establishing the Mars Network of communications/ navigation microsatellites in 1999.²¹ The JPL concept included launching microsatellites in pairs as secondary payloads on Ariane boosters, until six were in place. The satellites would carry UHF transceivers and omnidirectional antennas for use around Mars and Ka-band antennas for communicating with Earth.²²

The microsat constellation idea has resurfaced several times, as with the proposal made by the Canadian telecom firm Direct Leap in 2002.²³ NASA announced in 2004 that the Applied Physics Laboratory (APL) at Johns Hopkins would study a "Lunar Microsat Com-Nav Network."²⁴ It may be that a mix of solutions is preferable, and a dedicated exploration support constellation of PRISMs will be part of a larger network supplementing NASA's fully-stressed Deep Space Network by providing nodes near the Moon, Mars, or at Lagrange points.

High-resolution imaging of the Earth is done with medium-to-large spacecraft. These, however, have been supplemented by imaging from spacecraft like the DMC (Disaster Monitoring Constellation) of five microsatellites built by Surrey and now in full operation. The resolution of the DMC imagers on different satellites ranges from 32m to 2.5m.²⁵

Large spacecraft are preferred because, from orbital altitudes, Earth sensing requires large mirrors to detect correspondingly small objects on the surface through the obscuring and distorting effects of a thick atmosphere. This requirement is somewhat relaxed when imaging smaller bodies like Mars and the Moon, which have a thinner atmosphere or none at all. This is admittedly a gross simplification of a complex situation, but the varying conditions of smaller astral bodies put PRISMs back into the tradespace for examination.



Figure 3. 1999 JPL Mars Network Proposal (NASA)

A final note on this point is that, while large antennas and mirrors are required by physics for some functions, there have been numerous proposals to address this need through precisely aligned constellations of small spacecraft forming a "virtual aperture." What would have been the first test, the USAF's TechSat-21, was canceled in 2003 amid rising costs, but engineers continue to refine the concept and offer new techniques and configurations to provide precise apertures with less mass and energy.²⁶ As of 2004, no fewer than 39 "distributed" science satellite missions, ranging from simple constellations to tightly integrated, cross-linked networks, many using microsats, had been started or seriously proposed.²⁷

MIT envisions this function for future versions of SPHERES, although the positioning accuracy will have to be greatly improved. Since one-piece mirrors increase in cost with the cube of the diameter, distribution may be the only affordable approach to huge space telescopes.²⁸ The NASA Institute for Advanced Concepts (NIAC) is currently funding a study of a system which, by using laser thrusters and tethers, might permit 100-kg satellites to achieve nanometer positioning accuracies with a power expenditure under ten watts.²⁹

Sensing has much broader application than imagining, and often involves the study of phenomena around the target world rather than on the surface. NASA's ST-5 is an example of an environmental sensing mission using PRISM-type spacecraft. NASA's upcoming THEMIS (Time History of Events and Macroscale Interactions) mission will go a step further with a constellation of five larger microsats (with a dry mass of ~ 50kg and a similar amount of propellant) studying Earth's magnetosphere. Vice President Dan Mark of Swales Aerospace, which is building and integrating the spacecraft buses, has already noted, "This microsatellite technology has applicability for a variety of different space missions."³⁰

In March 2006, the U.S./Taiwanese FORMOSAT-3 (a.k.a. COSMIC) mission was orbited. It uses six 70-kg satellites carrying ionospheric photometers and GPS occultation receivers.³¹ Deriving atmospheric data from the occultation of GPS signals may be applicable to Mars if Martian navigation satellites are in place.

Task 5. Landers and Probes

The VSE and a variety of related reports and studies emphasize the need to "prepare the ground" for explorers by probing the Moon and Mars with additional robotic explorers.³² Work on the lunar phase of this effort, the above-mentioned LPRP, is already underway. One option for future exploration is to send relatively large numbers of small probes directly to the Moon and Mars to measure space environmental conditions en route as well as on arrival at the target bodies. For example, NASA's GeneSat-1, massing only 3kg, is awaiting launch to LEO to test the effects of space radiation on small organisms over time, and PRISMs of this type could be put in lunar or Martian orbit to provide data important to astronaut safety.³³

While important studies of moons and planets can be made during flybys or from orbit, physical contact is required to examine soil samples, confirm the firmness of a landing surface, etc. Using smaller landers, very attractive due to mass limits, depends on continued miniaturization of useful instrumentation. In April 2006, the Dutch firm Lionix BV displayed the Life Marker Chip, a single-chip laboratory able to look for organic molecules in soil samples. The chip will fly on ESA's 2011 ExoMars mission.³⁴ The Mars Instrument Development Project (MIDP) under NASA's Mars Technology Program, has been developing miniature instrumentation for use on Mars since 1998, producing everything from 10-gram UHF transceivers to 45-gram electronics packages for ground-penetrating radars.35

The idea of using small spacecraft to probe a desired surface area at multiple points is not a novel one. Two microprobes made up NASA's Deep Space 2 experiment, but were lost when their parent, the Mars Polar Lander, failed in 1999. NASA engineers at GSFC and Langley Research Center (LRC) centers have proposed the Autonomous Nano Technology Swarm (ANTS), a shape-shifting robotic pyramid so small it could be deployed in large numbers to Mars and other bodies using solar sails. A prototype of one of the individual vehicles, called the tetrahedral walker (TETwalker), has been field-tested on Earth.³⁶

In 2004, NASA funding was given to MIT's SPHERES team and its partner, Payload Systems Inc., to study the use of small, maneuverable satellites in Martian orbit to capture even smaller capsules holding Martian surface samples and launched into orbit from landers or rovers.³⁷ One of NASA's proposals for the next round of its Centennial Challenges is a \$2M prize to develop a micro reentry vehicle (RV) capable of bringing 1.5kg to Earth, accelerating "technology development that could lead to a routine method to return viable samples from orbital research platforms."38 Engineers from four nations have proposed a European Mars mission called Vanguard which would deploy a 36-kg base station lander and a 28-kg microrover with ground-penetrating "mole" probes.39

Task 6. Science

Overlapping with the Task 5 concept is that of independent microspacecraft science missions. The VSE described a robust, continuing program of robotic exploration to complement its "flagship" missions.⁴⁰ In addition to the roles just described, PRISMs may be used in independent scientific missions to the Earth-Moon-Mars neighborhood and throughout the solar system. ST5 and THEMIS (above) are two examples of relevant technology.

The use of microspacecraft to explore another celestial body began in 1958 with America's 38-kg Pioneer 1 lunar probe. The use of microsatellites to orbit another body goes back to the Apollo program. Apollo 15 and 16 each left a 36-kg Particles and Fields Subsatellite (P&FS) in lunar orbit to measure magnetic fields, charged particles, and variations in lunar gravitation. The most successful P&FS, Apollo 15's, was placed in an orbit of 102x139 km, where it operated for six months before an electrical failure occurred. The U.S. also launched three Explorer missions, two in the micro class, into lunar orbit so they could use the Moon to block radiation from Earth while studying cosmic and radiation other phenomena.41

In 2006, ARC proposed a lunar-orbiting microsatellite as one option for an auxiliary payload on the agency's large Lunar Reconnaissance Orbiter, although the idea was not selected. SSTL and ESA engineers have proposed a Venus probe with a mass of 8.1 kg, which includes 115 tiny atmospheric microprobes.⁴²

Stuart Eves of SSTL said in April 2006 that, "We see small satellites as the PCs of astronomy." Canada's 60-kg MOST astronomical satellite, launched in 2003, is currently looking for planets around Earthlike stars.⁴³ SSTL has studied small missions to Mars and Venus and maintains that microspacecraft can now provide the accurate positioning and pointing stability needed for many kinds of astronomical instruments. Surrey compares large science craft to mainframes and small ones to PCs and sees a role for both.⁴⁴

A logical response to the funding squeeze on NASA space science is the development of more science microspacecraft missions. In this case it is not "better, faster, cheaper," but rather the "go as you can pay" concept, "What's the most relevant and rewarding science we can do for the available dollars?"

SOURCES OF TECHNOLOGY

Most options for carrying out missions within the VSE require further advances in technology, and microspacecraft are not an exception. Some tasks will require an improved ability to recharge microspacecraft consumable resources such as battery power and thruster propellant fluid. A challenge for maneuvering microspacecraft is establishing the proper georeference frame for precise navigation, particularly at any significant distance from a parent vehicle. Despite the work done in the XSS, SNAP, and ASTEC programs, neither this capability nor automated rendezvous and docking (AR&D) has been mastered to the point of routine operations. A PRISM will be more sensitive than a larger spacecraft to the changes in mass or maneuvering characteristics that come with activities like depleting propellant, picking up or using a tool, or unintended impacts like thruster failure, and all these emphasize the need to continued improvement in self-sensing and control mechanisms.45

The funding issues that will no doubt continue to constrain VSE technology development make it vital to maximize the leveraging of technology developed by sources both inside and outside NASA. Fortunately, a great deal of relevant technology, at the spacecraft, system, and susbsystem levels, is available or in development from other programs, internal and external. Within NASA, the New Millennium Program (NMP) is charged with developing near-term technologies, while the NIAC looks at more exotic, long-term possibilities. NMP-supported missions have included the 2.4-kg Deep Space 2 probes and the recent ST5. Future missions include ST9, which (if funded) will further prove spacecraft formation flying technologies.

Proposals funded by NACI include the exploration of Mars by microprobes "seeded" by balloons and by microbots deployed at site of Martian caves.⁴⁶



Figure 4. Deep Space 2 Microprobe (NASA)

Several NASA centers have small-spacecraft expertise. GSFC is home to many robotic missions and to the Rapid Spacecraft Development Office (RSDO) and is working with LRC on the abovementioned ANTS concept.

For lunar programs, what is now the LPRP was moved from Ames to Marshall Space Flight Center (MSFC) in May 2006, but ARC will host a lunar projects office reporting to LPRP with the specific task of developing small spacecraft in support of the exploration effort.⁴⁷ ARC Director Worden, who was known for championing small spacecraft when he was in the Air Force, recently said of Ames, "We want to be the goto-guys for innovative, fast-paced, and affordable missions...We are going to offer NASA some lowcost propositions that will knock their socks off." As an example, he added, "For a few tens of millions, I'm convinced you can do low-cost lunar landers."⁴⁸

In May 2006, MSFC published a notice requesting concepts for miniaturized L-band (microwave band) radar antennas for use in sensing soil moisture, with the specific requirement that "Antenna design must be scaled to the proper weight and size to be deployable from current UAVs (unmanned aerial vehicles) with future follow-on work to embed the antenna into a microsatellite." MSFC's Charles Laymon explained, "The traditional science platform that NASA builds for a science mission has a long life of three to 10 years, incorporates a large number of instruments, and costs hundreds of millions of dollars," Laymon said. "These technologies can do things more cheaply. ... A UAV is a stepping stone in getting to a microsatellite."⁴⁹

JPL, which has worked on small spacecraft since Explorer 1 in 1958, proposed the Mars Network and worked on SPHERES along with ARC and MSFC. Johnson Space Center (JSC) has the lead for EVArelated programs and designed the Mini-AERcam. ARC also hosts NASA's Center for Nanotechnology, which states that nanotechnology will enable "Networks of ultrasmall probes on planetary surfaces, Micro-rovers that drive, hop, fly, and burrow, (and) Collection of microspacecraft making a variety of measurements."⁵⁰

There are many outside sources for NASA to draw upon as well. In addition to the specific programs mentioned above, Air Force Undersecretary Ron Sega has reemphasized the service's commitment to pushing the envelope of small-spacecraft technology. The Air Force envisions roles in near-Earth space for small, quickly-launched satellites providing advanced navigation, weather, communications, surveillance, and missile warning capabilities. This offers a promising, if not guaranteed, source of funding to continue developing microsatellite technologies with broad applications.⁵¹

Ball Aerospace is under contract to the USAF's Space and Missile Systems Center (SMC) for Space Test Program's Standard Interface Vehicle (STP-SIV).⁵² Papers published at the 2005 Conference on Small Satellites from a variety of sources, government and non-government, detail progress made in new miniaturized instruments and systems, including imagers, thermal control, star sensors, batteries, etc.⁵³ At the same meeting, Ecliptic Enterprises proposed its RocketPod external carrier/ejector, which is one example of the type of technology that could be used to carry tiny satellites on board larger missions.⁵⁴

Missile Defense Agency (MDA) programs are another technology source. MDA continues to develop its small ground-based kill vehicles, which push the state of the art in miniature electronics and sensors, and perform space experiments such as the 2007 Near Infrared Field Experiment (NFIRE), and microsatellite-based missile defense targets.⁵⁵ In 2004, MDA gave Space Dev a \$43M contract to "conduct a micro satellite distributed sensing

experiment, an option for a laser communications experiment, and other micro satellite studies and experiments as required in support of the Advanced System Deputate."⁵⁶

Military, civil, and commercial entities are also pushing ahead in the development of micro-electromechanical systems (MEMS): chip-size devices with nanoscale moving parts including actuators and sensors. Canadian space engineer Milind Pimprikar argues that MEMS have been adopted much more quickly into earthbound applications like automobile electronics than into aerospace. Pimprikar's company, Caneus NPS, Inc., has attracted over \$36M in U.S. and Canadian government funding to advance aerospace MEMS technology.⁵⁷ A near-term goal is a 10kg, \$3M MEMS-enabled nanosatellite for weather, imagery, and science applications, which would have obvious implications for miniature space probes.

Other companies including Swales, Microcosm, SpaceDev, AeroAstro, and General Dynamics C4 Systems (formerly Spectrum Astro), have either flown MEMS devices on satellites or are incorporating them into current designs. So are The Aerospace Corporation and government agencies including AFRL, DARPA, and the Naval Research Laboratory (NRL).



Figure 5. 10-kg MEMS-enabled Nanosatellite (Caneus NPS, Inc.)

Ideas also come from international sources. In addition to the Direct Leap proposal mentioned above, the British National Space Center funded a Mars Micro Mission Concept Study which produced such designs as the M-PADS mission, which would explore the Martian moons with a 16kg lander, and SIMONE, a "swarm" of 120-kg spacecraft to study Near-Earth Objects.⁵⁸

As mentioned earlier, the drive to produce low-mass, low-energy components and systems for microspacecraft should pay dividends for the larger spacecraft in the VSE. Some technology, such as thermal control systems, may not scale up directly from a small spacecraft to a large one, but at least some advances will. Dr. Rich Van Allen, who worked on large satellites at Hughes and now heads space system development for Microcosm, Inc., offered the example of a combined star sensor/IMU/GPS unit weighing only 3kg, which was built for a Department of Defense (DoD) microsatellite but could be used on a much larger craft.59

The Mars Technology Program's manager, Dr. Samad Havati, explained how microspacecraft technology will be useful to Mars and other planetary science missions even when such spacecraft are not used directly. Orbiter missions, while not as restricted in power and mass as landing missions, often use miniature versions of science instruments developed for observing Earth. Lander missions always benefit from reducing mass and will take advantage of any technology that serves that purpose. The most challenging science missions proposed for the Red Planet, Mars Sample Return flights, "are very much restricted in the amount of samples that they can bring back. Making the Mars Ascent Vehicle (MAV) lighter directly supports the increase in the amount of samples that are brought back."60

PRISM missions also offer the opportunity to test new technology and new operational concepts before committing to the expense and time involved in a large mission. This fits in well with the Aldridge Commission's emphasis on developing technology through a series of affordable iterations.⁶¹

Given current launch technology, spacecraft mass will always be, to varying degrees, a limiting factor in mission design. The use of microspacecraft as a technology source and flight testbed will help engineers deal with that limit on spacecraft of all sizes.

THOUGHTS ON MOVING FORWARD

Carrying out the grand challenge of the VSE requires that all options for performing VSE functions with smaller, lighter-weight spacecraft are actively pursued. At this time, there are several proposals for relevant NASA microspacecraft programs, like ANTS and MSFC's L-band Earth sensing microsatellite concept, but no one has the responsibility to look at microspacecraft technology across the breadth of the VSE and share that technology in accordance with a common vision.

Laying out this vision is a synergistic activity coupled to the development of the VSE architecture. As the architecting process expands beyond the ESAS study to encompass all aspects of the VSE, we suggest that NASA's Exploration Systems Mission Directorate consider the following actions at the appropriate times:

- Issue a Solicitation for Microspacecraft Concepts in Support of the Vision for Space Exploration.
- Host a workshop in which participants could offer and discuss ideas on this topic, followed by a joint NASA-industry working committee to select the most promising proposals and work with other offices in the ESMD to incorporate the VSE architecture into the PRISM programs and future budget submissions.
- Establish or designate an office to coordinate work on PRISM technologies and programs while working with industry to ensure promising technologies are identified and shared across the different programs.
- As a near-term target for a practical demonstration, select one or more PRISM-type missions to be incorporated into the LPRP.
- Hold an annual PRISM workshop to further facilitate coordination and report on progress of individual efforts.

CONCLUSIONS

This paper has presented recent developments in microspacecraft technology and utilization and discussed the missions and uses in which they may be advantageous to carrying out the VSE. While microspacecraft are not suitable for those VSE missions requiring large spacecraft for reasons of physics (e.g., high-resolution optics) or capacity (e.g., crew and bulk cargo transport), they do show promise as part of the tradespace for many other tasks involved in the VSE.

There are two fundamental truths about the VSE. One is that executing it within practical cost limits will be very difficult. The second is that it must not fail. It is no exaggeration to say the Vision could be the opening act of an era of exploration, discovery, and colonization which can be one of the great achievements of the human race. If the VSE effort fails, though, whether due to costs, accidents, or other reasons, it may be decades before the political will to begin another such program develops. Accordingly, those carrying out the Vision - in NASA, in industry, in academia, and internationally - must examine every practical option for technologies that save money, increase safety, or improve the science to be done in the VSE. We believe that there are enough common technologies and ideas in the microspace field to warrant examining the role of microspacecraft holistically across the many programs and missions involved in executing the VSE.

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