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# Cubesats: Cost-effective science and technology platforms for emerging and developing nations

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**Abstract**

The development, operation, and analysis of data from cubesats can promote science education and spur technology utilization in emerging and developing nations. This platform offers uniquely low construction and launch costs together with a comparative ubiquity of launch providers; factors that have led more than 80 universities and several emerging nations to develop programs in this field. Their small size and weight enables cubesats to "piggyback" on rocket launches and accompany orbiters travelling to Moon and Mars. It is envisaged that constellations of cubesats will be used for larger science missions. We present a brief history, technology overview, and summary of applications in science and industry for these small satellites. Cubesat technical success stories are offered along with a summary of pitfalls and challenges encountered in both developed and emerging nations. A discussion of economic and public policy issues aims to facilitate the decision-making process for those considering utilization of this unique technology.


*Keywords:* Cubesat; Developing countries; Innovation; Capacity building; Space technology; Nanosatellite

## 1. Introduction

People from developing and emerging nations often struggle to obtain clean water, sufficient nutrition, adequate healthcare, effective education, economic stability, and basic security. Expenditures on space science and satellite technology in such countries may, therefore seem inappropriate because of the need for diverting resources from near-term social programs. Nevertheless, long-term economic prosperity depends in part on intellectual capital, the advancement of which requires scientific training as well as the use, and eventually the development, of new technology. We posit that a recent technological advance, the cubesat, can contribute on a politically attractive and economically viable basis to the expansion of an emerging nation's intellectual capital. Cubesat technology offers a uniquely inexpensive pathway to the study of scientific phenomena and the advancement of novel engineering concepts in the unique environment of outer space.

Primarily for economic reasons, satellite development has been dominated heretofore by the United States, Russia, members of the European Union, Japan, Canada, China and India. Satellites in general, and the smallest of them in particular, are less expensive to develop and build than full-size spacecraft. A growing number of private commercial and public (both military and civilian) space launches carry ever more small "secondary" payloads into orbit at far lower cost than the dedicated missions required by conventional satellites.

Smallsats including cubesats have spawned significant commercial activity, including providers of complete satellites, components, and launch services, many of them starting as academic spin-offs (Table 1). An early success story is the collaboration between Pumpkin, Inc., and Stanford University leading to the development of the Cubesat Kit. Commercial success has undoubtedly been furthered

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Table 1
Selected small and startup cubesat, component, and service providers.

| Company | Products and/or services | Date founded, location |
| --- | --- | --- |
| Surrey Space, Ltd. | Small satellites | 1985, UK |
| Tethers Unlimited | Tether technologies for orbital formation flying | 1994, US |
| SpaceQuest, Inc. | Cubesat components | 1994, US |
| Pumpkin, Inc. | Cubesat kits and integration services | 1995, US |
| Sinclair Interplanetary | Attitude determination & control for smallsats | 2001, Canada |
| MicroSpace | MEMS microthrusters | 2002, Italy |
| Dobson Space Telescope GbR | Telescopes and imagers for small satellites | 2002, Germany |
| Clyde Space | Cubesat Kit components and design services | 2005, UK |
| TriSept Corp. | Small satellite launch integration services | 2006, US |
| ISIS | Small satellites and launch integration services | 2006, The Netherlands |
| GOMSpace | Small satellites | 2007, Denmark |

Selected Small and Startup Cubesat, Component, and Service Providers.
Surrey Satellite Technology LTD., http://www.sstl.co.uk/About_SSTL/Our_Story.
Tethers Unlimited, http://www.tethers.com/index.html.
SpaceQuest communications components, http://www.spacequest.com/products/CCS-100.pdf.
Pumpkin Inc., http://www.cubesatkit.com/content/pumpkin/about_pumpkin_inc.html.
Sinclair Planetary, http://www.sinclairinterplanetary.com/.
Micro-Space, http://www.micro-space.org/company.html.
Dobson Space Telescope, http://www.dobson-space-telescope.com/2-0-about.html.
Clyde Space, http://www.clyde-space.com/about_us/staff/craig.
Space Access Technologies, http://www.access2space.com/.
ISIS, http://www.isispace.nl/index.php?option=com_content&task=view&id=17&Itemid=32.
GOMSpace, http://www.gomspace.com/index.php?p=profile.

by public-domain access to the cubesat standard, along with the availability of graduates with education and experience on this platform.

Reduced costs to participate in space activities have spurred small satellite development programs throughout the world by the governments, industry, and particularly the academic institutions of a growing number of nations with both advanced and emerging technological capabilities, including Algeria, Argentina, Brazil, Colombia, Egypt, Indonesia, Iran, Israel, Malaysia, Mexico, Nigeria, Pakistan, South Africa, South Korea, Turkey, and Venezuela; some of their achievements were recently discussed (Wood and Weigel, 2009).

Universities pioneered the development of the smallest of the small satellites—the "nano" and "pico" categories to which cubesats belong.[1] Conventional satellite development is capital and expertise intensive, requiring multi-year development and large professional teams, thus severely limiting participation by science and engineering students. Recognizing this as particularly problematic for aerospace engineering students, Jordi Puig-Suari of California Polytechnic Institute (Cal Poly) and Robert Twiggs of Stanford University introduced the cubesat specification[2]: a 10-cm cube with mass of no more than 1 kg (see Fig. 1). In this paper, we use a more recent, broader definition of cubesats, including those that exceed 1 kg per cube as well as two- and three-cube spacecraft.

Since the cubesat's introduction, the comparatively low cost of space research projects and engineering development activities that fit within the size, mass, and power constraints of satellites less than 10 kg has attracted some 80 educational institutions around the world to this field. Cubesat technology development has been significantly accelerated in recent years, in universities as well as government and industry, by rapid advances in nano-, micro-, and miniature technologies in fields including telecommunications, (opto)electronics, materials, sensors, fluidics, and instrumentation. These advances have helped enable many small but remarkably capable autonomous instruments and systems to accomplish a variety of remote measurements and experiments in cubesats (Kramer and Cracknell, 2008) (see Section 3).

Fig. 1. Cubesat model (credit: ESA – A. Reyes).

[1] Mass-to-orbit is a principal cost driver in space flight, hence a common classification metric. Small satellites weigh less than 1000 kg and are subclassified: mini, 100–1000 kg; micro, 10–100 kg; nano, 1–10 kg; pico 0.1–1 kg; femto <0.1 kg.

[2] Cubesat Design Specification (CDS), http://www.cubesat.atl.CalPoly.edu/images/developers/cds_rev12.pdf.

Though pioneered in universities, the potential of nanosatellite technology has not been lost on governmental space and research agencies. The National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) in the USA operate successful cubesat programs, further described in Section 3. The European Space Agency (ESA), through its Education Office, sponsors the Student Space Exploration and Technology Initiative (SSETI) program and the annual European Cubesat Workshop, where students learn satellite development and exchange best practices (ESA SSETI, 2010).

The cubesat represents a paradigm shift for the traditional space industry: this technology can be "disruptive," displacing larger conventional satellites in a number of applications (Swartwout, 2004). Perhaps for this reason, even medium and large aerospace corporations are entering this arena, such as Orbital Sciences Corporation, primarily a launch service provider, which in 2006 introduced TJ3Sat, the first cubesat in development entirely by secondary school students (OSC, 2009). Aerospace giant Boeing has flown its own cubesat, the Cubesat TestBed 1 (CSTB1) (Boeing, 2009) and offers, without cost to nonprofits and academic organizations, a structural frame that conforms to the cubesat specification. The frame accommodates single- and multi-cube configurations; users must agree to share changes and improvements with the cubesat user community (MacGillivray, 2009).

For nations with emerging technology sectors, cubesats can foster private business development with comparatively small capital outlays, or offer expansion markets for existing firms. Cubesat startup ventures provide cost models that some developing and emerging nations may be able to emulate, in part, to establish or expand fledgling aerospace sectors.

The United Nations (UN) plays a key supportive role in the cubesat arena, and since 1995 has formally recognized the benefits small satellites and, more recently, cubesats provide to developing and emerging nations (UN COPUOS, 1995; Othman, 2003; Balogh and Haubold 2009); indigenous satellite technology can complement and extend UN initiatives that deliver space technology for developmental benefit. Starting in 2009, the UN Basic Space Technology Initiative (BSTI) established a three-year symposium series, Small Satellite Programmes, a forum for the exchange of strategies to identify space applications for countries not traditionally involved in such endeavors, as well as the UN/IAA (International Academy of Astronautics) Workshop on Small Satellite Programmes at the Service of Developing Countries (UNOOSA, 2010).[3] The Disaster Management Constellation (DMC) is one example of small satellites providing remote sensing imagery to the UN Space-based Information for Disaster Management and Emergency Response (SPIDER) (UN-SPIDER Portal, 2010). The UN Institute for Training and Research (UNITAR) utilized DMC imagery to develop maps used in flood water management in the Caprivi Region of Namibia (DMCii, 2009).

This article summarizes cubesat technology, provides examples of their scientific impact, and illustrates how cubesat programs can provide near-term benefits via applications such as environmental monitoring, disaster response, and telecommunications while helping developing and emerging nations to promote science education and hasten technology development.

## 2. Cubesat configurations, technologies, subsystems, and operations

In this section, cubesat configurations are summarized, along with key technologies that are contributing to their rapid advance and widespread adoption. Overviews of how cubesats travel to, and are deployed in, outer space are presented together with essentials and constraints of operation in the unique space environment, as well as control and communication with the ground.

### 2.1. Configurations and technologies

Most spacecraft comprise a payload, which is transported to and through space in order to execute a measurement, experiment, or other task, and a "bus" that includes critical support functions to operate the spacecraft: command and control; communications; propulsion; attitude determination and control; de-orbit mechanism; power generation and distribution; energy storage; data buffering and storage. Cubesats include varying subsets of these functions; their small size may blur the physical distinction between payload and bus. Of the common configurations—1U, 2U, and 3U, each "U" being a 10-cm cube—the larger two lend themselves to the dedication of one cube to the bus, the other(s) to the payload. These three cubesat configurations are driven in part by launch-vehicle integration-and-deployment hardware, the most widely used being the Cal Poly P-POD (poly-picosatellite orbital deployer), discussed in more detail below. Fig. 2, NASA Ames' GeneSat-1, is a 3U cubesat including one bus cube and a two-cube experimental biology payload. This nanosatellite typifies the integration of multiple recent technological innovations and the advance of cubesats into new scientific disciplines.

The breadth of cubesat applications has increased dramatically in the past decade due in part to advances specific to the conventional satellite industry, and in larger measure due to general technological progress in rapidly evolving fields including microelectronics, low-power communications, high-efficiency solar cells, low-cost precision fabrication, high-energy-density batteries, microelectromechanical systems (MEMS), high-density memory, field-programmable gate arrays, miniature high-efficiency motors and

[3] More information available:http://www.oosa.unvienna.org/oosa/en/SAP/act2010/graz/index.html.

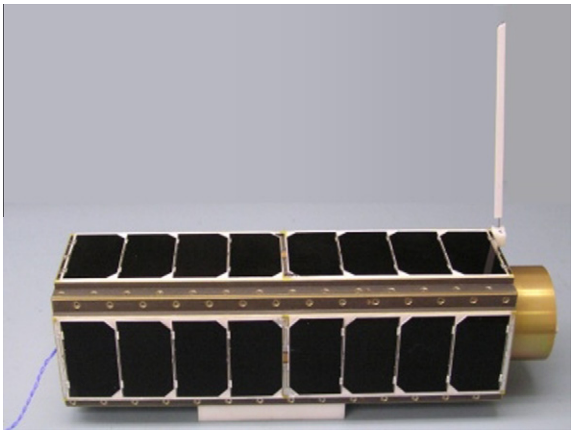

Fig. 2. NASA Ames 3U, 4.6-kg Gene-Sat-1 (credit: NASA Ames Research Center).

actuators, advanced materials, integrated optics, microsensors, and microfluidics. Often, commercial off-the-shelf (COTS) components are used without modification to develop the various cubesat subsystems; the overall design of the cubesat and the density at which the subsystems are integrated, as well as methods of assembly and ruggedization, are often the requirements unique to operation in the space environment. Nonetheless, subsystems and instruments developed for demanding industrial and consumer environments often need minimal modification for use in small satellites. For example, a typical consumer mobile telephone "drop" requirement, 1 m onto a concrete floor (Xie et al., 2003), produces shock levels well in excess of those required for launch and deployment on and from typical space vehicles.

### 2.2. Launch providers, services, and orbits

Arguably the single most important reason to design a cubesat-based space mission is the number of reasonable-cost opportunities to deliver it to space. Table 2 catalogues some of the recent proliferation of available launch access options. The cubesat specification has helped reduce the resources required to launch and deploy small satellites (Toorian et al., 2008), but requirements remain for general project administration, integration with the launch vehicle, and regulatory compliance, all costing time and demanding relevant experience. Launch providers generally require certification of suitability for vehicle integration, including acoustic, vibration, thermal, and vacuum testing: the "paying customer" for the launch does not want the primary payload damaged by a mechanically deficient secondary "hitchhiker" payload. Although there are new rideshare opportunities such as the NASA Educational Launch of

Table 2
Launch providers and secondary payload accommodations.

| Launch vehicle | Provider | Launch sites | Secondary payload adapters and accommodations |
|---|---|---|---|
| Atlas V, Delta IV | NASA/ULA, USAF | CCAFS,[a] VAFB[b] | Optional EELV[c] secondary payload adapter |
| Dnepr | ISC Kosmotras | Baikonur[d] | Five P-PODs demonstrated |
| Falcon 1 | SpaceX | Kwajalein,[e] CCAFS | Ride Share Adapter; six P-PODs maximum |
| Minotaur I | USAF (OSC[f]) | VAFB, Wallops FF[g] | Carries one or two P-PODs/launch |
| Minotaur IV | USAF (OSC) | Kodiak,[h] VAFB | Maximum of four P-PODs planned |
| Neptune 30 | IOS Inc.[i] | Eua Isle, Tonga | Maximum of four 1U or two 2U cubesats |
| PSLV,[j] GSLV[k] | ISRO[l] | Satish Dhawan SC[m] | P-POD, number not available |
| Taurus XL | NASA (OSC) | VAFB, CCAFS, WFF, Kwajalein | Maximum of three P-PODs planned |
| Vega | ESA | Kourou, Fr. Guiana | Maximum of three P-PODs planned |

Launch Providers and Secondary Payload Accomodations.
IOS (2010). Neptune30 payload & Spaceport Tonga. Retrieved from IOS: http://www.interorbital.com/index.html.
ISC Kosmostras (2010). Dnepr Launch Vehicle. Retrieved from ISC Kosmotras: http://www.kosmotras.ru/en/rn_dnepr/.
Russian Space Web (n.d.). Dnepr 7th launch campaign 2006. Retrieved 2010, from Russian Space Web: http://www.russianspaceweb.com/dnepr_007_belka.html.
OSC. (n.d.). OSC Publications: Taurus Specifications. Retrieved 2010, from OSC: http://www.orbital.com/NewsInfo/Publications/taurus-user-guide.pdf.
ESA. (2009). ESA sponsors CubeSat launch opportunity on Vega debut . Retrieved 2010, from ESA: http://www.esa.int/SPECIALS/Education/SEM3N03MDAF_0.html.
[a] Cape Canaveral Air Force Station, Florida USA.
[b] Vandenberg Air Force Base, California USA.
[c] Evolved Expendable Launch Vehicle.
[d] Also known as Tyuratam, located in Republic of Kazakhstan.
[e] SpaceX launch facility on Omelek Island in Kwajalein Atoll, Republic of the Marshall Islands.
[f] Orbital Sciences Corp.
[g] NASA Wallops Flight Facility Wallops Island, Virginia, USA.
[h] Kodiak Launch Complex, Kodiak Island, Alaska, USA.
[i] Interorbital Systems.
[j] Polar Satellite Launch Vehicle.
[k] Geosynchronous Space Launch Vehicle.
[l] Indian Space Research Organization.
[m] Satish Dhawan Space Center.

Nanosatellites program (NASA ELaNa, 2010), launch providers consider cubesats to be secondary payloads. Cubesat developers therefore must defer to the primary payload mission profile. Lack of dedicated space access for cubesat developers will continue to be a major limitation on utilization unless one or more of the nano-launch vehicle initiatives cited herein are implemented.

The value of providing launch vehicle integration and regulatory certification expertise has been recognized by several academic and commercial entities, including Cal Poly, Innovative Solutions In Space (ISIS), Surrey Ltd., and University of Toronto Institute for Aerospace Studies (UTIAS), who now offer such services. ISIS, for example, integrated four cubesats that were launched successfully on September 23, 2009 by an Indian rocket (PSLV C14) (ISIS, 2009). Utilizing third-party providers frees focus and resources for cubesat design and development.

A recent entrant, aiming to provide low-cost space access for academic research, is InterOrbital Systems (IOS), marketing an alternative to cubesats dubbed the TubeSat Personal Satellite (PS) Kit, with three-quarters of the mass (0.75 kg) and volume of a cubesat. To comply with space debris-mitigation guidelines, IOS plans for TubeSats to orbit at about 310 km, which, depending on atmospheric and other conditions, provides an orbital lifetime of up to one month. Launches are to begin in the first quarter of 2011 (Milliron, 2010).

The US Department of Defense (DoD), with an estimated excess mass capacity of 16,000 kg over the next five years, established the Space Test Program (STP) as a one-stop coordinator for military experimental satellites serving the needs of US armed services, defense agencies, and selected non-military NASA and private small-satellite projects; STP will provide secondary payload access for NSF-sponsored cubesats. What percentage of the 16-ton capacity may be reserved for national security purposes is unknown, but even a small percentage represents many opportunities for cubesat space access (Bourne and Williams, 2009). Access to any US launch vehicle requires State Department approval for non-US entities, and STP approval is case by case; the process can be facilitated by a third-party launch services provider such as Cal Poly. Along similar lines, the Russian Space Agency (RSA) insists each payload be certified to have no military capability.

Through its Education Office and Launchers Directorate, ESA sponsors space access opportunities. The Vega rocket, for example, will debut with nine cubesats in late 2010 (ESA, 2009), and ESA's VERTA program includes five demonstration launches of the Vega, providing a number of secondary payload opportunities (ESA Launchers, 2010).

Cubesats are most commonly delivered to low Earth orbit (LEO), defined as 160–2000 km above the Earth's surface; other orbital details are typically determined by the destination of the primary payload. Choice of orbit is further constrained by current guidelines adopted by the UN Inter-Agency Space Debris Coordination Committee (IADC), with which all major space-faring nations are now harmonized: satellites are to either actively or passively deorbit within 25 years after launch.[4] Without active manuevering or de-orbit capability (see Section 2.4), a cubesat is therefore altitude limited, depending on its ballistic coefficient (mass, cross-sectional area) and solar effects on upper atmosphere density, to 500–600 km.

### 2.3. Deployment systems

Key to the success of the cubesat concept is the possibility of isolation from the primary payload and launch vehicle that allays launch provider concerns of potential damage to, or impediment to the deployment of, the primary payload. The most widely used solution is Cal Poly's P-POD, a standard mechanism that attaches a cubesat to a primary payload or launch vehicle. The P-POD, essentially a box with a spring-loaded "kicker-plate," ejects the cubesats in "jack-in-the-box" fashion when the door is opened by electrical command. Certified for a wide variety of launch vehicles, the P-POD/Mark III accommodates up to three individual 1U cubesats or one 3U configuration.[5] Another cubesat deployer, the UTIAS X-POD,[6] supports the cubesat standard while accommodating non-longitudinal configurations as well, e.g. a 20-cm cube for the CanX-6 nanosatellite. The X-POD deployed eight nanosats on the Indian PSLV.

New standard launch vehicle interfaces for satellites in the micro and mini classes can indirectly benefit cubesat deployment. For example, CSA Engineering, under a US Air Force small business grant, developed an EELV secondary payload adaptor (ESPA) ring to support one to six secondary satellites, up to 181 kg each, between a primary payload and a Delta IV or Atlas V launch vehicle (CSA Engineering, 2010). The existence of SPAs spurred development of multiple P-POD deployment systems (i.e., adapters for the adapter), including the NPSCuL (10 5U P-PODs, ESPA compatible) and NPSCuL-Lite (eight 3U P-PODs) from the US Naval Post Graduate School. In principle, swarms of 40 or more cubesats could be deployed by combining such adapters.

[4] UN IADC-02-01 Space Debris Mitigation Guidelines 10-15-2002;NASA-STD-8719.14 change 4, 9-14-2009; RSA General Requirements to Spacecraft and Orbital Stages on Space Debris Mitigation 1-1-2009; ESA ADMIN/IPOL/2008-2 Annex 1 and 2 Space Debris Mitigation for Agency Projects; IADC members: Italian Space Agency (ASI), British National Space Centre (BNSC), Centre National d'Etudes Spatiales (CNES), China National Space Administration (CNSA), Deutsches Zentrum fuer Luft-und Raumfahrt e.V. (DLR), European Space Agency (ESA), Indian Space Research Organisation (ISRO), Japan Aerospace Exploration Agency (JAXA), National Aeronautics and Space Administration (NASA), National Space Agency of Ukraine (NSAU) and Russian Aviation and Space Agency (Roscosmos).

[5] P-POD Mk III Interface Control Document (ICD) http://www.cubesat.atl.calpoly.edu/.

[6] UTIAS/SFL XPOD Technical Specifications http://www.utias-sfl.net/SpecialProjects/XPODindex.html.

### 2.4. Propulsion and de-orbit systems

The extremely limited mass, volume, and power available on cubesats severely constrain propulsion systems, which to date have been limited to mechanisms to increase drag (atmospheric or magnetic) in order to hasten the deorbit process, thereby complying with space debris mitigation standards—an issue of increasing importance to cubesat developers (Spacenews, 2009a,b,c). De-orbit concepts demonstrated to date exploit atmospheric drag by increasing the surface area of the satellite once on orbit: AeroCube 2 and 3 picosats used an inflatible balloon to shorten orbital life from a nominal 1–3 years to 2–3 months (PicoSat-Portal, 2010). The NASA Ames O/OREOS 3U cubesat (Ehrenfreund et al., 2009) will use a simple spring-deployed "sail" that stows in a $10 \times 10 \times 1$ cm volume; when deployed, it resembles a box kite made with aluminized polymer panels, increasing surface area by 60% (NASA Ames, 2010).

For deorbiting purposes, electromagnetic tethers connect a satellite bus to an electrical conductor (or a second satellite); the tether is charged, actively or by collecting electrons present in the (inner) Van Allen belt. The motion of this charged conductor produces a magnetic field opposing Earth's field, creating drag. The first cubesat with a tether was DTUSat-1, with which contact was lost after it reached orbit; the project closed (DTUsat, 2004). The ambitious Multi-Application Survivable Tether (MAST) flight experiment aimed to depoly three nanosats along a 1-km tether, demonstrating tethers for on-orbit maneuvering, but full deployment had not been confirmed as of May 2007 (Hoyt et al., 2007). Tethers Unlimited announced in 2009 a commercial de-orbit mechanism, nanoTerminator, mountable on any face of a 1U cubesat and comprising a conformal solar array module and a 30-m conductive tape. This device is claimed to allow cubesat orbits as high as 1000 km while maintaining compliance with space debris guidelines (Hoyt et al., 2009).

Other cubesat-appropriate technologies have been developed that could provide minimal orbital maneuvering, e.g. for formation flying, but have not operated in orbit. Vacuum arc thrusters were part of the ill-fated Illinois Observing NanoSatellite (ION) (Rysanek and Hartman, 2002); colloid thrusters (Busek, 2010), electrospray technology (Lozano, 2004), and pulsed-plasma thrusters (Zhuang et al., 2009) have been developed as well. Sandia National Laboratories developed a monopropellant microthruster using electrokinetic pumping and catalytic decomposition of liquid anhydrous hydrazine to deliver controlled-thrust pulses with a maximum continuous thrust of 1.5 mN, minimum impulse bit of 7 μN s, and an average specific impulse of 110 s (Patel et al., 2008). Fig. 3 shows a MEMS cold-gas thruster developed by MicroSpace; it has a thrust range of 100 μN to 10 mN, mass of 300 g, 2 W maximum power draw, and pointing resolution of 0.1″ (Micro-Space, 2010).

Fig. 3. A MEMS cold gas thruster (credit: Micro-Space.org).

### 2.5. Attitude determination and control systems

An attitude-determination-and-control system (ADCS) measures the orientation of the satellite and either maintains or adjusts that orientation as appropriate for mission requirements. ADCSs are of two classes: passive and active. A variety of sensors determines orientation, and a range of actuators maintains or changes attitude. Passive systems utilize the space environment to naturally orient the satellite; the most common approach among cubesats (e.g. on XI-IV, Mea Huaka, GeneSat-1, CAPE-1, Delfi-C3, PharmaSat, QuakeSat, UWE-1) (EO Portal, 2010) is a combination of permanent magnet(s) that orient one end of the satellite towards the closer of the Earth's magnetic poles (often used to point radio antennas), plus magnetic hysteresis rods, oriented so as to damp nutation or "wobble" in satellite motion, again by interaction with the geomagnetic field. As a 3U cubesat with this attitude control mechanism passes from the northern to southern hemisphere and back again, typically every 45–50 min (orbits are 90–100 min), it slowly rotates so that the magnetic rods point, like the needle of a compass, towards the magnetic north or south pole, whichever is closer. The 3U cubesats also rotate about their long axis at a rate of 1–2 rpm. Another approach to stabilization is use of the gravity gradient, which was implemented by Quakesat.

Remote sensing, including imaging, often requires active ADCS (Vega et al., 2009). Until recently, high-performance ADCSs were not possible in cubesats due to power, mass, and volume constraints, but a number of ADCS components are now becoming available for cubesats. Magnetotorquers, momentum wheels, and even miniature thrusters (Section 2.4) can be purchased. UTIAS in partnership with Sinclair Interplanetary offers a complete turnkey ADCS and sensor package (UTIAS SFL, 2010). The trend in active systems is three-axis control to support more challenging mission requirements; a comparatively sophisticated three-axis ADCS, including sun sensors, magnetometer, magnetorquers, momentum wheel, liquid-$SF_6$-fuelled cold gas propulsion system was flown on the Canx-2 3U cubesat

(Rankin et al., 2004). The tradeoffs in the various ADCS options are generally performance and capability against complexity, size, and cost.

### 2.6. Electronics and power; radiation considerations

Most cubesats successfully utilize COTS electronic components. So-called "MIL-SPEC" (US military specification) versions of some components, available at additional cost, offer a lower probability of failure due to more rigorous standards of manufacture and test, and often a wider operating temperature range. Fortunately, in LEO below 3000 km (most cubesats orbit below 1000 km), radiation levels are modest due to shielding by Earth's magnetosphere, and much of the radiation present can be shielded by a few mm of aluminium plate. At altitudes above 3000 km or for long-duration missions (exceeding several months), however, space radiation may require engineering design—primarily shielding and component choice, but even alteration of the choice of circuit architecture—to prevent degradation or failure of electronics; discoloration of optical elements can become a consideration as well. When "radiation-hardened" electronic components are not available at reasonable cost, radiation testing of components and subsystems can be accomplished at low cost utilizing medical radiation sources, e.g. the Loma Linda Proton Treatment Center in California or iThemba Labs in Cape Town, South Africa. The Proton Therapy Cooperative Group maintains a listing of such facilities (PTCOG, 2010).

Average power generation and consumption for cubesats ranges from 2 TO 6 W (time averaged) for 1–3U nanosatellites using "body-mounted" (fixed, non-deployed) solar panels, as on AAUSAT-2, GeneSat-1, and PharmaSat (EO Portal, 2010). Deployable solar arrays, such as those on QuakeSat and the quadruple array of Delfi-C3 (EO Portal, 2010), offer (much) greater power generation at a cost of increased complexity and risk of deployment failure. Several concepts are now in design or prototype stages that integrate solar arrays with de-orbit mechanisms, with potential for 20–60 W of power generation in full sunlight (Silver et al., 2009). Cubesats are excellent platforms for cost-effective testing of new power generation technologies: the Dutch Delfi-C3 triple unit cubesat, for example, is testing advanced thin-film solar cells with a planned efficiency of 12% and a goal of 50% cost reduction and 50% increase in power-to-mass ratio (EO Portal, 2010). Triple-junction solar cells with efficiencies above 30% are available commercially (Spetrolab, 2010; Emcore, 2010).

Batteries play a key role in the operation of cubesats: typical orbits expose the spacecraft to the Sun for about 2/3 of each 90–105 min orbit, so continued function during eclipse requires energy storage. Lithium-ion battery technology is well suited to this task in terms of energy density and comparatively little "memory" effect: they do not have to be fully discharged before being recharged, but, as in laptop use, they do have to be appropriately managed for charge/discharge cycles and thermal parameters: depending on orbital parameters, heaters may be needed at times to keep the batteries in their operating temperature range. Even when the satellite is in the sun, batteries can help bridge temporarily high power demand, such as when the radio is transmitting or a heater is warming a cold experimental subsystem to operating temperature.

### 2.7. Communications

The communications subsystem is critical: it receives operational commands from the ground and transmits data. The nature of a cubesat mission can dictate the type of communications systems and vice versa. One remotely acquired image, for example, can range from tens to thousands of kilobytes, while the measurement of physical parameters—magnetic fields, temperatures, light intensities, accelerations, etc.—typically require a few bytes per data point. Capacious memory and COTS processors consistent with cubesat power limitations enable onboard data storage and compression, adding flexibility to the downlink

Table 3
Selected cubesat communications performance parameters.[a]

| Cubesat | Communications frequency | Downlink power | Data rate[b] |
|---|---|---|---|
| Masat-1[d] | Downlink 438 MHz/uplink 435 MHz | 200 mW | 1200 bps |
| Cute-1 | DownLink1 436.8 MHz | 100 mW | 1200 bps |
| | DownLink2 437.47 MHz | 600 mW | |
| CP2 | Downlink 437.3 MHz | 500 mW | 1200 bps |
| GeneSat-1 | Downlink/uplink 2.4 GHz frequency-hopping | 1 W | 1200 baud |
| | UHF beacon[c] (transmit only) | 500 mW | |
| CanX-2 | Downlink 2-4 GHz (S-band) | 500 mW | 32 kbps to 1 Mbps |
| | Uplink UHF Amateur Radio | 1 W | 4 kbps |
| | VHF beacon | | 15 WPM |

[a] Adapted from Klofas et al. (2009).
[b] bps = bits per second; baud = successfully received bits per second; WPM = words per minute.
[c] In the satellite communications context, a beacon is an autonomous, broadcast-only radio typically used to help locate the satellite after deployment; as demonstrated by GeneSat-1 and other cubesats, packets of data can be carried on beacon pulses as (partial) backup for data downlinking via the primary radio.
[d] MASAT-1. MASAT-1. Retrieved 2010, from MASAT-1: http://cube-sat.bme.hu/?page_id=25&lang=en, 2010.

process. Table 3 lists typical cubesat communications performance parameters. The communications subsystem can consume 50% or more of the total available power budget when transmitting, which typically occurs for only a matter of minutes per day when the satellite is in the line of sight of the ground station (see Section 2.8). A challenge for communications with cubesats is their high rate of motion in LEO relative to ground stations. The quality of the link therefore varies considerably during a pass overhead—which may last only a few minutes—limiting the amount of data downlink; mitigating research is ongoing with some success (Caffrey and Palmer, 2009).

2U and 3U cubesats can accommodate more sophisticated communications subsystems than their 1U counterparts. For example, CanX-2, a 3U cubesat, has three communication transmitters: a VHF beacon, a high-data-rate S-band transmitter, and a full duplex amateur radio transmitter. The S-band transmitter has a dynamic data rate of 32 kbps to 1 Mbps dependent on the link condition (Shah et al., 2009).

Cubesats are beginning to broadcast images and voice data, an example being the SEEDS cubesat of Nihon University; their website encourages public participation by enabling amateur radio operators to request transmission of a voice message (Yamazaki et al., 2008). The cubesat OUFTI-1 will be the first satellite to demonstrate the D-STAR communications protocol in space (OUFTI-1, 2010).

The relationship of amateur radio[7] and cubesats is noteworthy: nearly all cubesats use this portion of the frequency spectrum for beacon purposes, and often for data uplink/downlink as well. For non-commercial, publicly accessible use, obtaining a permit for amateur radio allocation is considerably less complex than the process commercial satellite operators must follow to obtain frequency allocations through the International Telecommunications Union (ITU). The relatively low cost of amateur radio equipment has led to its wide adoption by cubesat projects for ground station communication.

PCI-compliant, low-cost, high-capability analog/digital converters and field-programmable gate arrays enable emulation of most conventional radio hardware functions using software. Software-defined radio can reduce power consumption and mass while improving flexibility and efficiency, at a cost of longer (software) development times. The University of Louisiana at New Orleans' is developing the second in its series of cubesats, the CAPE2, to test software-defined radio (Barousse and Oliver, 2009), and the Spanish Ministry of Science is co-sponsoring development of the Xatcobeo cubesat, which will test a software-reconfigurable radio; it is scheduled for launch on the maiden flight of the European Vega (Xatcobeo, 2010).

### 2.8. Ground Stations

A major challenge when operating a cubesat is obtaining useful data on Earth in a reasonable time period (days–months). Satellites in LEO travel across the visible sky at high rates, hence the window of visibility at typical cubesat altitudes is typically a few minutes per "pass" over a ground station, and for typical orbits there may be just one-three such passes per day. It is also important to note that, with the common magnetic-rod-based passive attitude control described in Section 2.5 causing a slow "tumble" of the satellite every 1/2-orbit, a radio antenna on one end of the satellite is useful only for passes over ground stations in one hemisphere (northern/southern). Limited power for cubesat radios also throttles downlink rates (see Table 3), and because most university projects can afford only one or two ground stations with "small" (e.g. 3-m) antennas, uplinking and downlinking of data are further limited.

Partially addressing such limitations, the internet, low-cost standard communications hardware, and open-source software have enabled a proliferation of ground station networks supporting educational satellite operations. ESA, through its Education Office, sponsors the Global Educational Network for Satellite Operations (GENSO) project (Fig. 4), a peer-to-peer client server network of ground stations interconnected via the internet. GENSO's distributed nature allows ground stations to increase the daily amount of satellite visibility; an educational satellite project can elect to participate in GENSO and utilize any participating ground station. This approach has tremendous potential for global ground station access and, eventually, near-continuous periods of satellite communication (GENSO, 2010).

Another ground station network is the non-profit University Space Engineering Consortium (UNISEC) GSN-WG (ground station network working group), with thirteen Japanese universities and four additional participating institutions in the US, Sweden, Taiwan, and Germany. UNISEC has standardized software, released for public use in 2007 (UNISEC, 2010), for ground station management and web-enabled services.

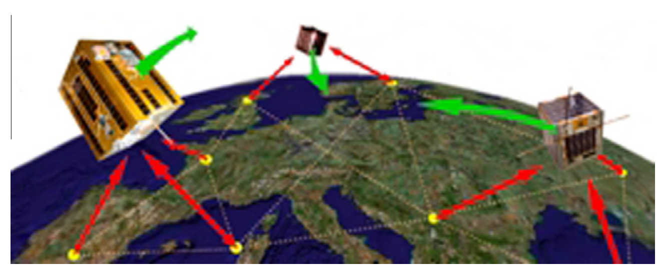

Fig. 4. GENSO ground station network.

[7] Amateur radio, often called Ham radio, is supported by organizations worldwide, and has been active for nearly a century. Recently, amateur radio has been closely coupled to student education in satellite communications, providing redundant ground station services or verification of cubesat beacons following on-orbit deployment. Ham operators are licensed by local governments and communicate with other operators as a hobby or for public service. The ITU has allocated bands in the HF, VHF, UHF, and microwave portions of the spectrum for amateur radio.

Developing a dedicated ground station provides greater independence at a financial cost. For example, UTIAS Space Flight Laboratory (SFL) developed a ground-station network with sites in Toronto, Vancouver, and Vienna, Austria; the cost of developing one ground site in this network with automatic satellite tracking is several tens of thousands of Canadian dollars (Tuli et al., 2006). An exemplary entry-level ground station was a student project at the University of Hawaii, for which a senior undergraduate designed a mobile ground station that successfully tracked cubesat XI-IV, Cute-1, and QuakeSat; the work is a model of resourcefulness (Ichikawa, 2006). At the other end of the cost spectrum, development time can be minimized by the purchase of a commercial turnkey system, such as the complete VHF/UHF-capable ground station available for purchase online from ISIS cubesatshop.com. Several South American countries are developing cubesat ground station networks, an example being the HERMES-A/MINOTAUR project sponsored by the Ecuadoran Space Agency, which integrates cubesats with the internet (EXA, 2010).

## 3. Cubesats for science research, technology validation, and commercial application

The utility of cubesats as scientific research and technology validation platforms is now increasingly recognized, and developers are responding with instrumentation capabilities normally applied on larger satellites. Table 4 lists a non-comprehensive sampling of science and technology applications of flight-proven and planned payloads, revealing a wide range of science and technology missions executed by well-known as well as non-traditional, actors in space technology.

### *3.1. Astrobiology*

Astrobiology is the study of the origin, evolution, distribution, and future of life in the universe. Cubesats enable exposure of micro-organisms, as well as organic compounds—particularly those considered potential building blocks of biology, or biomarkers—to astrobiologically important aspects of the space environment, including solar vacuum ultraviolet and ionizing radiation. These studies are key to understanding how such compounds and organisms survive in, or are modified by, the space environment. While similar studies have been carried out on the International Space Station (ISS) with post-flight ground analysis (Ehrenfreund et al., 2007; Cottin et al., 2008; Horneck et al., 2010), cubesats can go to orbits where the radiation dose is significantly higher (at least one order of magnitude) than on ISS; they can be oriented such that the average daily duration of solar UV exposure is much longer. Cubesat experiments can continue for many months in orbit and, with *in situ* measurement technology, the dynamics of space-induced changes can be continuously monitored, rather than being limited to simple before-and-after-flight comparisons. *In situ* measurement also obviates the need for "downmass" (bringing a payload back from ISS), a capability in chronic short supply. NASA's Organism/Organic Exposure to Orbital Stresses (O/OREOS) cubesat weighs approximately 5 kg and includes two independent science payload instruments to study space environmental effects on organic compounds and the time-dependent viability of living organisms in space, see Fig. 5. O/OREOS features a 1/2-cube UV–visible-NIR spectrometer (200–1000 nm, <2 nm resolution) developed commercially (Aurora Design Technology, 2010).

A study on micrometeorites in LEO will be conducted by the Romanian Goliat Mission, expected to be launched on the maiden flight of the European VEGA.

Although used exclusively in LEO to date, cubesat technology offers particular promise as the basis for a new generation of light-weight, low-cost, self-contained instruments suitable for piggyback payload opportunities to near-Earth objects, interplanetary space, the Moon, Mars, and elsewhere in the solar system. Whether they remain in orbit as free-flying spacecraft or are delivered to a remote surface for *in situ* studies, cubesats can help address evolutionary questions, identify human exploration risks, and study planetary protection[8] concerns.

### *3.2. Astronomy*

An example of the application of nanosatellites in astronomy, BRITE (BRIght-star Target Explorer)/CanX-3 (Canadian Advanced Nanosatellite eXperiment-3)/TUGSAT-1 is a collaborative mission of UTIAS/SFL, the Technical University of Graz, Austria, and the Institute of Astronomy at the University of Vienna, Austria. This pair of small satellites[9] is designed to utilize photometers with specific filters for synchronized asteroseismology observations: pressure and gravity waves in the interior of pulsating stars affect their frequency spectra. Analysis of such data provides insight about the star's core composition, size, age, and internal structure (Deschamps et al., 2006).

### *3.3. Atmospheric science (see also Earth observation)*

Many cubesat-appropriate opportunities exist for the study of atmospheric sciences. The recently-launched SwissCube will study atmospheric airglow phenomena using an innovative optical telescope as the primary payload (SwissCube, 2010). The US NSF has funded the

[8] Planetary protection is the principle that seeks to prevent contamination of other solar system bodies by life from Earth, or protect the Earth from contamination by possible lifeforms as a result of activities involving interplanetary space missions. For more information visit the NASA Planetary Protection website, http://www.planetaryprotection.nasa.gov/pp/.

[9] UniBRITE and BRITE-AUSTRIA (TUG-SAT1) are the two 20-cm-cube nanosatellites of the BRITE constellation.

Table 4
Sampling of completed and proposed nanosatellite science and technology missions.

| Category | Mission | Sponsor/lead agency | Status[a] |
|---|---|---|---|
| Astrobiology | **O/OREOS:** UV–visible spectral monitoring: organic materials; space radiation effects on survival/growth of 2 microbes | NASA/ARC | In progress, L = 5/2010 |
| Astronomy | **BRITE/CanX-3/TUGSAT-1:** Constellation of nanosatellites for asteroseismology | CSA/U. Vienna/Austrian Research Promotion Agency (FFG) | In progress, L = 2011 |
| Atmospheric Science | **SwissCube:** telescopic investigation of atmospheric airglow phenomena | Ecole Polytechnique Federale de LauSanne | L = 9/2009, nominal operation |
| | **AtmoCube:** Interaction between space radiation and upper atmosphere[d] | Univ. Trieste and commercial sponsors | In progress, L = 2011 |
| | **FIREFLY:** Terrestrial gamma-ray flashes induced by lightning | NSF | In progress |
| | **RAX:** Plasma interactions of the thermosphere | NSF | In progress |
| Biology | **GeneSat-1:** *E. coli* gene expression via fluorescent reporters in microgravity | NASA/ARC, Stanford University, Santa Clara University | L = 12/2006, full mission success |
| Earth observation | **QuakeSat:** Measure extra-low freq. magnetic waves from earthquakes in space | | L = 6/2003, nominal operation |
| | **PRISM:** Validation of medium-resolution earth observation | University of Tokyo | L = 1/2009, nominal operation |
| Ecology | **NCube2:** Large ship AIS[b]; reindeer tracking (**NCube1** was destroyed at launch) | Norwegian U. of Science and Technology | L = 10/2005, no comm. established |
| Electronics | **Robusta:** Validate test standards for space radiation impact on electronics | CNES/ESA/Montpellier University | In progress, L = 2010 |
| Materials Processing | **HawkSat 1:** Commercial materials processing research | Hawk Institute for Space Sciences | L = 5/2009, no communication |
| Pharmaceutical Efficacy | **PharmaSat:** Antifungal agent dose response of yeast in microgravity | NASA/ARC, U. Texas Medical Branch, Santa Clara U. | L = 5/2009; full mission success |
| Technology Demonstration | **CANX-2:** Tech. eval.: propulsion system, radios, attitude sensors/actuators, GPS receiver, IR spectrometer for pollution | UTIAS/SFL, CSA | L = 4/2008, technology demonstration success |
| | **Libertad-1:** Colombia's 1st satellite; test of basic systems | Universidad Sergio Arboleda | L = 4/2007, successful; deactivated |
| | **MAST:** Electromagnetic tether technology demonstration | Tethers Unlimited | L = 4/2007, partial communications only |
| | **NANOSAIL-D**: 3U cubesat to demonstrate solar propulsion | NASA/Marshall Spaceflight Center | In progress, L = 2010 |
| Space Weather | **CINEMA**[c] detection of sub-atomic particles from space magnetic storms | UC Berkeley Space Sciences Lab/ Imperial College/NSF | In progress |
| Telecommunications | **NEMISIS** survey spectrum 1–1300 MHz: document radio-frequency interference | US Naval Academy | In progress |

[a] "L" = launch.
[b] AIS = automatic identification system.
[c] CINEMA = cubesat for ions, neutrals, electrons, and magnetic fields.
[d] AtmoCube. AtmoCube. Retrieved 2010, from University of Trieste Cubesat project, AtmoCube: http://www2.units.it/~atmocube/, 2010.

RAX 3U cubesat to examine interactions of plasma electrons in the lower polar thermosphere; (RAX, 2010) it is hoped a better understanding of these interactions will provide strategies to mitigate communications disruptions (EO Portal, 2010). FireFly, a collaboration between Boston University, Montana State University, and the Aerospace Corporation, also funded by NSF, will study terrestrial gamma-ray flashes induced by lightning (FireFly, 2010).

### 3.4. Biology

Space biology examines the effects of the space environment on terrestrial life. Microgravity affects mammals in various ways—altered fluid distribution, immune stress, bone density decrease, muscle atrophy—but not even the smallest mammals are likely to fly anytime soon aboard size-constrained cubesats. Cells and microorganisms in culture, however, are also affected: the absence of gravity impacts nutrient and waste transport, altering growth rates and metabolic processes. Space also carries significant risk of biological damage from high-energy ionizing radiation, which is greater outside Earth's magnetosphere (altitudes above ~70,000 km), but can be significant even at the 300–800 km altitudes frequented by cubesats. Synergies between microgravity and radiation effects have been reported (Nelson, 1996; Canova et al., 2005).

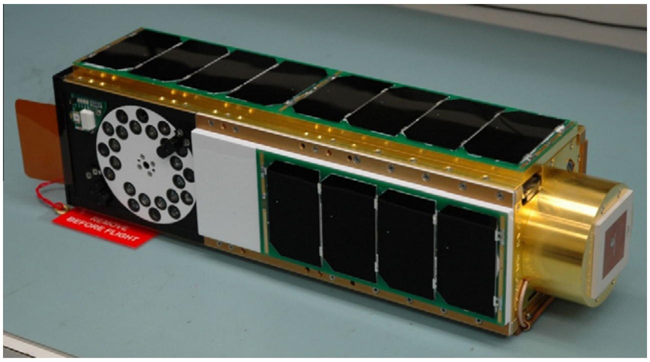

Fig. 5. NASA Ames O/OREOS 3U satellite, which includes two independent payload instruments (1U each) and a 1U bus. The patch antenna is visible at the right end of the satellite; the circular array of organic sample cells at the left end of the satellite is exposed directly to space. (credit: NASA Ames Research Center).

Cubesats are well-suited to the study of fundamental space biology using well-understood model microorganisms such as *E. coli*, *S. cerevisiae*, *C. elegans*, *Drosophila melanogaster* and *Arabidopsis*. Such studies help elucidate effects relevant to long-duration human space travel, help characterize potential mutations of microbes and pathogens present in space habitats (Castro et al., 2004; Klaus and Howard, 2006), and help in planning therapies to treat illness or injury in space.

GeneSat-1 launched in December of 2006 as a secondary payload on a Minotaur I rocket (Ricco et al., 2007). *E. coli* were maintained in stasis for ~5 weeks prior to launch and deployment: cubesats that support living biology have to date required organisms to be held in stasis for weeks prior to launch due to requirements of launch vehicle integration. Data returned from LEO by GeneSat-1 demonstrate renewal of *E. coli* growth in a multiwell fluid culture environment with monitoring of culture population via optical density and tracking of gene expression via green fluorescent protein assay. In May of 2009, PharmaSat, utilizing the same 3U form factor as GeneSat-1, launched and deployed in LEO. The 48-microwell biology experiment characterized the dose-response of *S. cerevisiae* to the antifungal drug voriconazole using 3-wavelength optical measurements (Parra et al., 2009).

### 3.5. Earth observation

Cubesats can serve as extremely low-cost remote sensing platforms, and instrumentation technology advances along with innovative designs are enabling cubesat remote sensing applications. For example, spectrometers, once considered incompatible with the mass and power limitations of cubesats, are now commercially available and flight proven (see Section 3.1). Another example, the CANX-2 cubesat (3 kg), used its Argus IR spectrometer to analyze atmospheric gases (pollutants and greenhouse gases) over Ontario, Canada, in December 2008, covering a one square km sample area. The Argus has a 900–1700 nm spectral range, mass of 230 g, and dimensions of $5 \times 6 \times 8$ cm (Thoth, 2010). It was designed to validate detection of gaseous species by sampling the radiance response due to solar radiation absorbed by Earth's atmosphere (Sarda et al., 2006).

In June of 2003 QuakeSat, a 3U cubesat ($11 \times 11 \times 35$ cm) was launched into an 840-km sun-synchronous, dawn-dusk orbit (Flagg et al., 2004). It was designed to show feasibility for on-orbit detection of extremely low frequency (ELF) magnetic field disturbances emanating from Earth: in the early 90s, anomalous ELF signatures were reportedly detected by satellites prior to and after large earthquakes. The primary payload instrument aboard QuakeSat, an induction magnetometer, was designed to extend as a telescopic boom following spacecraft deployment.

PRISM is an Earth-imaging validation mission developed and operated by the University of Tokyo (Fig. 6). PRISM's $19.2 \times 19.2 \times 40$ cm (stowed) dimensions are beyond the cubesat realm, but its mass of 8.6 kg is in the nanosatellite class. PRISM's main payload is a narrow-angle camera (NAC) with CMOS imager having a panchromatic design resolution of 10 m and a field of view of 6.5 km$^2$; a linear actuator moves the CMOS imager board along the focal line of the NAC. Upon attaining

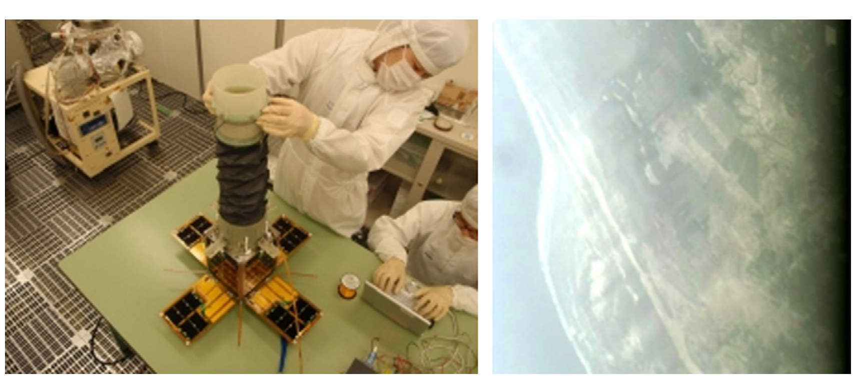

Fig. 6. PRISM cubesat and image taken over the coast of western Mexico. PRISM image centered approximately Lat. +24°41′37.73″, Lon. −107°57′18.33″ closely matches image accessed from Google Maps October 10, 2009. PRISM image available: http://www.space.t.u-tokyo.ac.jp/prism/main-e.html.

orbit at 660 km (98° inclination), PRISM deployed a 90-mm-aperture lens mounted on an extendable boom; onboard wide-angle cameras confirmed deployment and allow calibration of satellite attitude.[10] PRISM utilizes deployable solar arrays for power; a 3-axis ADCS uses magnetorquers to provide the necessary stability for Earth imaging (Tanaka et al., 2009). Fig. 6 shows PRISM with NAC deployed and an image by PRISM of roads and other terrestrial topography. The resolution of such images is adequate to identify and map vegetation and agricultural crop type, and this sort of data can help identify correlations between environmental factors and human disease vectors such as the mosquitoes that transmit malaria and yellow fever (Beck et al., 2000).

Cubesat imaging could be applied to directly save lives during crisis responses (disaster management). For example, following the Kashmir Earthquake of 2005, satellite imagery was crucial for disaster response teams to assess earthquake damage and determine which roads remained open to deliver aid. Images provided through the UN rapid mapping network were on the order of 15 m resolution (esa.int, 2005), potentially within reach of the capabilities of a cubesat: Pumpkin, Inc. advertises a turnkey 7.5-m-resolution imaging system, MISC, based on a 3U cubesat (Kalman et al., 2008); Dobson Space Telescope is developing a 1.2-U telescope with 6-m resolution, claimed to be suitable for use in a 1U cubesat (Dobson Space Telescope, 2010).

### 3.6. Ecology

The NCube2 by the Norwegian University of Science and Technology was designed and launched to monitor animal population dynamics via space-based tracking of radio collar transmitters on reindeer (EO Portal, 2010). Ecological field studies could exploit the large geographical coverage and frequent revisit rate of LEO cubesats, which can be affordably dedicated to small niche studies with correspondingly small budgets; using large monolithic spacecraft for such monitoring would be cost prohibitive. Countries such as Tanzania, Kenya, or Uganda, whose economies strongly depend on tourism related to their indigenous wildlife populations, might enhance their national conservatory programs using cubesats for remote monitoring; dedicated cubesat ecological studies could have promotional value in their own right.

### 3.7. Electronics

With their rapid development life cycles, cubesats provide unique opportunities to iteratively improve electronic technology for aerospace applications. The educational value of electronic testing on cubesats is also important to note: for many components, developing a small integrated system for *in situ* component analysis is straightforward, involving the measurement of temperatures, voltages, currents, and/or logic outputs. This can be a good "starter" project for those initiating their first space science and technology activities.

For example, Robusta, billed as "le satellite qui s'expose" (Table 4) will validate test standards for space radiation effects on electronics at a cost of ca. €30,000 ($41,000), not including sponsor hardware donations and launch as a secondary payload on the ESA Vega's maiden flight. It is a "simple" 1U, ~1-kg cubesat mission led and developed primarily by a university group.

### 3.8. Materials processing

Development of novel materials and processing methods in microgravity could create new intellectual property, perhaps even open new markets, and cubesats are a means by which emerging and developing nations could share in such opportunities. The ISS is the preferred platform for its long-duration, hands-on access opportunities, but access is costly and limited, particularly for those not among the group of nations that manage ISS activities. In addition, the ISS environment is vibrationally "noisy" due to onboard machinery, human activities, etc., so the microgravity environment is less than perfect. Other, affordable microgravity platforms such as sounding rockets, parabolic flights, and high-altitude balloon drops have the disadvantage of limited duration.

Cubesats as materials development-and-processing research platforms have the advantages of reasonable cost, access for a broader group of participants, long-duration microgravity (months, even years), exceeding even the typical ISS experimental durations, and a remarkably "quiet" vibrational environment. The principle limitation of the cubesat platform for this purpose is sample return: characterization of newly developed materials must be carried out *in situ* using analytical methods that fly along with the materials experiment. The US HawkSat-1, developed by the Hawk Institute for Space Sciences (Table 4) (Hawk Institute, 2009), a 1U cubesat, was developed primarily as a technology demonstration, but also was to expose a number of material samples to space, record the effects of exposure, and telemeter the data to the ground station.

### 3.9. Space weather[11]

The importance of monitoring and understanding space weather is well recognized by the developed world due to its impact on telecommunications and national electrical grids. Space weather awareness is arguably important to developing and emerging nations as well, since their

[10] Available literature implies image resolution actually obtained on orbit is greater than the design resolution of 10 m but less than 30 m. Exact resolution has not been cited.

[11] Space weather comprises the changing environmental conditions in (primarily) near-Earth space, including dynamic phenomena involving ambient plasma, magnetic fields, radiation, and other matter in space.

national infrastructures often depend on satellite and cellular communications networks. Furthermore, space weather is not globally uniform: the South Atlantic Anomaly (SAA), for example, sits above parts of South America and southern Africa, and has the most impact on satellites passing directly through it. The dynamics of the SAA could therefore be of particular importance to nations reliant upon overhead satellites that must communicate or image while inside the SAA.

An example of the use of a nanosatellite for space weather research is the CINEMA collaborative effort (Table 4) a pair of 3U cubesats that will conduct stereoscopic detection of sub-atomic particles resulting from space magnetic storms (NSF, 2010).

### 3.10. Technology demonstration

Relative to large satellites, cubesats can further the development of technological expertise or the validation of new technologies with substantially less risk and resources. Many of the diverse science applications summarized earlier in this section (see Table 4) are either technology demonstrations or their first successors, not surprising given the newness of the cubesat platform. The nation of Colombia's first space mission, the Libertad-1 cubesat, was developed in-house by an academic institution and is an entry-level technology familiarization mission. Ambitious missions targeting cutting-edge technology include the MAST experiment to validate electro-magnetic (EM) tether propulsion (Section 2.4) and CANX-6, demonstrating on-orbit tracking of AIS[12] beacons, an application that has attracted the attention of entrepreneurs in the US, with several startups now offering remote infrastructure monitoring services (AprizeSat, 2010).

#### 3.1.1. Telecommunications

Some developing and emerging countries may have good reason to establish indigenous telecommunications services based on cubesats, in part due to limitations in terrestrial communications infrastructure. For example, communications demand along the African coast is on the rise, with bandwidth demand forecast to increase by 50% from 2008 to 2016. The high cost of bandwidth hampers UN efforts such as the SchoolNet Africa project, which advocates internet access for African schools (Spacenews, 2009a,b,c). The UN Office for Outer Space Affairs noted satellite bandwidth charges were one of the largest obstacles to "tele-education" (UNOOSA, 2006). Promising developments in cubesat formation flying, advanced communications techniques, and multi-cubesat launch capability could enable a nation to place a minimal communications constellation in space at comparatively low cost. Such constellations may not support relay of video or bulk voice, but certainly can support text content such as instant messages and email, providing limited "telecommunications independence."

Although oversize relative to cubesats, four of Aprize Satellite, Inc.'s 25-cm cube, 11-kg "almost-nano" satellites fly in a constellation in LEO for a range of infrastructure applications, including monitoring propane tank levels via a store-and-forward message system (PERC, 2008).

Responding to ever-increasing electromagnetic interference due to the proliferation of low-cost radio equipment, particularly in amateur radio bands from unlicensed operators, the US Naval Academy Satellite Lab has proposed NEMISIS. This 1U cubesat would adapt a commercial handheld tuneable wideband receiver to survey the spectrum from 1 to 1300 MHz for "harmful" interference sources that affect satellite communications systems in the VHF and UHF ranges (US Naval Academy, 2010).

## 4. Implications for STEM education, technology innovation, and science

The discussion to this point has covered the description and capabilities of the cubesat platform, activities by universities and entrepreneurs, secondary payload opportunities offered by space launch providers, and various organizations promoting increased utilization of cubesats through ground station networks. Now the focus turns to implications for education in science, technology, engineering, and math (STEM), technology innovation, and science.

### 4.1. STEM education and workforce development

The economic prosperity of a nation depends in part on the intellectual capital of its people. One aspect of such capital is the ability to innovate and utilize technology, which in turn depends on educating youth to be the workforce of tomorrow.

Space programs by their very nature are holistic endeavors that marshal intellectual capacity from many disciplines across science and engineering. The UN Office for Outer Space Affairs (UNOOSA), through its UN/Austria/ESA Symposia on Small Satellite Programmes for Sustainable Development (Graz Symposia), has recognized the role of small satellites for sustainable development through building a "critical mass of professionals" (UN COPUOS, 2009).

The following are examples of policy implementations that current space-faring and non-space faring countries pursuing industrial development may consider, with emphasis on impassioning youth to pursue study and careers in science and technology:

- Encourage participation of secondary-school-level students with university-level cubesat programs where appropriate. This is consistent with pedagogical theory that engendering passion for learning, particularly in

[12] Automatic Identification Sytems (AIS), see US Coast Guard, http://www.navcen.uscg.gov/?pageName=typesAIS.

the sciences, is enhanced if youth are encouraged earlier rather than later in their education. An example of such a project is the TJ3SAT and cubesat project developed entirely by secondary school students of Thomas Jefferson High School, Fairfax, Virginia, USA (OSC, 2009).
- Support participation in amateur radio activities. The Radio Amateur Satellite Corporation (AMSAT.org) made history with the successful launch on December 12, 1961 of its indigenous OSCAR 1 satellite with mass of 120 kg. AMSAT is active today in cubesat development. AMSAT also has an active role providing tracking and communications redundancy support to cubesats. Amateur radio provides for participation in space activities and experience with underlying technologies while having a relatively low cost for entry compared to actual cubesat development (AMSAT, 2010).

Key success criteria for the aforementioned policy strategies, particularly for youth, include: ensuring hands-on experience with tangible hardware; collaborative activities; publicizing accomplishments. The issue of analyzing, sharing, and publicizing results is addressed by the plethora of free visualization, social networking, and collaborative technologies accessible on the internet. If there is any doubt as to the enthusiasm students have as members of a cubesat project, one only needs to visit YouTube.com and search on keyword “cubesat”.

An effective strategy to develop a sustainable science- and technology-proficient workforce is to link STEM education programs with the country’s development priorities, ensuring that each new generation of scientists and engineers is gainfully employed. How this linkage is enabled, and the relation to the opportunities afforded by cubesats, is discussed next.

### 4.2. Technology capacity and innovation

The literature on economic development often links technology capacity with innovation. Innovation strategies distinguish between technology push and market pull. A push strategy is research and development that does not necessarily satisfy market demands. In contrast, a pull strategy is research and development in response to market demands.

Remote sensing is an example of market pull that addresses the needs of agriculture, ecotourism, land management, and, indirectly, health services for developing countries. USAID considers agricultural development a critical engine of economic growth, recognizing the need to develop a capacity for agricultural science and its commercial implementation, agribusiness. In poorer countries, about 75% of the population live in rural areas and many rely on subsistence farming (USAID, 2010). In other cases, countries such as Tanzania export cash crops like coffee. In either situation, an understanding of the relation of weather, hydrology, and land management to agriculture can mitigate starvation—whether in the literal or economic sense. An enabler for this capacity is remote sensing, which has been proven to be a boon to agriculture in developed countries. Several decades ago, 20–30 m lateral resolution was adequate for estimating crop productivity, but demand for higher resolution has increased since accurate crop financial valuation requires higher resolution. Moreover, demand for visit frequency to a given parcel has increased to every few days, allowing farmers to take preventive action to protect crops and plan irrigation (Murthy, 2009). Both demands are within the capabilities of current remote sensing providers, but at significant cost. If cubesats prove to be effective remote sensing platforms, they may provide significant cost advantages whether operated indigenously or under a fee-for-service approach.

The application of remote sensing for ecotourism using cubesats potentially has direct economic benefits. Many developing nations have unique environments and ecologies that support current tourism markets or may support new tourist destinations. Remote sensing products utilized in geospatial information systems (GIS) enhance management of current ecotourism destinations or identification of new tourist sites (Kumari et al., 2010). Ecotourism in developing nations such as Kenya, Uganda, and Tanzania is one of the top industries, and improved wildlife management contributes to the sustainability of tourism. Cubesats have successfully tracked AIS radio signals of wildlife on land and could be applied by developing countries relying on littoral ecotourism.

Communications infrastructure is critical to a nation’s economy. Developing nations have addressed this need by bypassing wired infrastructure and investing in cellular networks. Since cellular networks require satellite “backhaul” to interface with external networks beyond their immediate national borders, developing nations are in a sense already dependent on space technology. As mentioned previously, high bandwidth costs (satellite or terrestrial) are considered by the UN to be a major obstacle for current distance-learning initiatives in Africa. A possible market-pull strategy to satisfy bandwidth demand would be to develop indigenous satellite communications capacity. This can be an expensive proposition both monetarily and in terms of expertise. However, the increasing utility of cubesats and the ability for multi-satellite deployment allows for the possibility of LEO communication constellations of modest capability and cost relative to larger satellites. An example of the implementation of this concept is the HUMSAT project, a proposed constellation of cubesats providing store-and-forward communications with cooperative ground sensors and leveraging the existing GENSO ground station network. The main HUMSAT project goal is to facilitatie *in situ* climate measurements using low-data rate communications for areas with minimal or no telecommunication infrastructure for the primary purpose of humanitarian aid. HUMSAT was selected as a UN project during the 2nd UN/Austria/ESA Symposium on Small Satellite Programmes for Sustainable Development (HUMSAT.org, 2010).

Software in cubesat subsystems, as for larger satellites, is critical to the successful operation of the satellite and management of the payload. Cubesats provide low-cost platforms for gaining practical, real-world experience in software algorithm development, understanding of real-time data management, control-theory, and software–hardware interfaces. This expertise is directly transferable to many job skill sets in the information technology (IT) market. Space technologies, and cubesats in particular, are but an element of a much broader portfolio of science and technology capacity-building strategies.

### 4.3. Science capacity

As discussed previously (see Section 3), there is ample demonstration that cubesats are viable platforms for a wide variety of science measurements. Studies consistently identify causal links between investment in science research and innovation, and economic development. There is consensus that basic research is beneficial to agriculture (Evenson et al., 1979; Fernandez-Cornejo and Shumway, 1997). Still, a reasonable question to ask is 'Why support remote sensing using cubesats when limited resources can be applied to research in agricultural science?' The answer is that the lower overall costs of cubesats compared to larger satellites may allow countries to support both approaches in their efforts to improve agricultural science.

Another reason countries may consider conducting science using cubesats is that space offers an unique experimental environment. Experiments on the Space Shuttle recently revealed increased virulence of *Salmonella typhimurium* grown in microgravity (Wilson et al., 2007), and similar results obtained under the NASA ISS National Laboratory Pathfinder missions for *Salmonella enterica* have initiated space experiments in support of the development of a vaccine for salmonella (NASA, 2010 National Lab Pathfinder). Currently, there is no salmonella vaccine available for human use. Aside from being among the most common causes of food poisoning world-wide, salmonella is a major cause of childhood death in third-world nations (Becker, 2009). Initiating a full-scale research program on the ISS is likely beyond the resources or commitment level of countries with developing or emerging science-and-technology capacity, but mission examples from Section 3 demonstrate that non-traditional space actors can engage in ground-breaking basic science with modest resources through the opportunities afforded by cubesats. Governments and institutions of poorer nations now have more options to pursue science from, and in, space.

## 5. Economics of cubesat technology

Space activities are very expensive and include a high degree of risk. Building and launching a full-scale satellite platform with instruments for experimental science can cost $200 million and up. A general industry estimate for building and fully testing space instruments is about $1 million/kg. Cubesats are a relative bargain, with total costs ranging from $200,000 to $2 million each, and as Table 5 below illustrates, the total cost/kilogram (development, integration, launch) is approximately half that of large experimental science payloads.[13] They are less expensive because they are small, light in weight, (1–5 kg each), and usually single-purpose instrument platforms. Of course, cubesats are not as capable as their full-size counterparts, but they offer unusually interesting opportunities for scientists, universities, and others who cannot afford either the long lead-time or the large cost of traditional satellite research efforts.

The space industry is still in the early stages of developing cubesat technologies. As is typical of most innovations, the first products cost much more per unit than their successors. The total cost of $4 million for NASA's GeneSat-1, for example, included laboratory work to develop multiple bio-payload concepts. Follow-on satellites typically do not incur the same start-up costs as their predecessors, which can include purchasing and establishing various development, test, and integration capabilities, as well as mission ground-support infrastructure. For example, PharmaSat has a cost of $3 million and the O/OREOS cubesat cost is $2.5 million (AstroBio Net, 2009; NASA, 2010). Both are NASA satellites and both are more complex than GeneSat-1 and all of these are 3U systems. Several factors are working together: (1) a learning curve effect reduces costs and development time as scientists, engineers, and technicians improve their skills with new technology; (2) economies of scope are realized as different types of cubesats are managed under the same leadership, and (3) economies of scale come into play as parts and equipment can be ordered in multiples when satellites can share components.

Since cubesat technology is relatively new and there are comparatively few cubesats in operation today (32 cubesats on orbit as of May 2010)[14] (Puig-Suari, 2010), it is premature to evaluate the economic supply and demand conditions in rigorous terms. It is also premature to estimate many cost factors, since there is no standardization for the functions of cubesats, nor is there a standard launch price or launch vehicle for cubesats. There are many launch options including dedicated smaller launch vehicles, secondary payloads on larger vehicles, and other "piggyback" and "hitchhiker" possibilities.

However, even though the total cost of building and launching a cubesat payload is far cheaper than more traditional satellites, and the price charged for a small payload may reflect a discount (either as goodwill to the research community or because the marginal cost of a secondary

[13] Most of these estimates are for US Government satellites. There are offerings of private picosatellites as low as $8000 (see www.interorbital.com/index.html), but comparisons are difficult since the instruments aboard the cubesat differ greatly in purpose, sophistication, and cost.

[14] Although some 80 universities worldwide are pursuing cubesat development only a relatively small number have reached orbit since space access is an ongoing challenge (see Section 2.2).

Table 5
Average costs for cubesats.

| Sponsor | Satellites | Average cost per kilogram |
|---|---|---|
| National Science Foundation[a] | RAX, FIREFLY, DICE, FIREBIRD, CINEMA, REPTile | $385,000 |
| NASA[b] | GeneSat-1 (4.4 kg) | $870,000 |
| | PharmaSat (5.1 kg) | $590,000 |
| | O/OREOS (5.5 kg) | $455,000 |
| Other cubesats | XaTcobeo, QuakeSat, MAST, Libertad-1, NRO, DTU-1 (1U and 3U) | $510,000 |
| Overall average | | $560,000 |

[a] Costs for these NSF 3U cubesats do not include integration with launch vehicle, launch, and ground operations.
[b] Costs for these NASA 3U cubesats include integration with the launch vehicle, launch, and ground operations.

payload on a launch vehicle with mass margin is very low), the true cost/kilogram of putting cubesats into space is the same as for any other launch payload. These costs range from about $3,000 per kilogram for the converted Soviet ICBM Dnepr vehicle to over $30,000 per kilogram for the Pegasus (Orbital Sciences Corp., US). Some governments and companies may offer otherwise-unused capacity on launch vehicles for less money, and in fact often do so in preference to flying ballast mass that is needed to balance the spacecraft but serves no other purpose, and generates no revenue. In the long run, if the demand for launching cubesats increases beyond ballast-replacement and similar secondary opportunities, the supply of such discounted launches may be less than the demand for them, pushing the price upward. It should also be noted that these are prices charged to customers, not the actual cost of building and launching the vehicles. The labor component of the scientists and engineers designing the cubesats is also no less expensive than other highly skilled space personnel (in developed countries), at least within any given country. Nonetheless, there is a degree of scaling of such design costs with the size of the instrument: a 5-kg cubesat requires orders of magnitude less design time than the Hubble Space Telescope.

In the design and development of cubesats, there are, however, several important distinguishing and unique elements that help to reduce the costs of their construction. The first is standardization on a common form factor and the accommodation for modularized internal components that provides inherent advantages like elimination of redesign of the structural bus for every mission. This has created a marketplace of commercial component suppliers, which has led to reduced development costs. For example, having a standardized form factor and nanosat mass range enabled the development of the P-POD deployment mechanism that has resulted in increased flight opportunities through ride-shares, ultimately resulting in more rapid science- and technology-demonstration projects.

The second factor is that the altitude range of a cubesat that is typically below 1000 km, where there are lower levels of space radiation relative to the medium, geosynchronous, and other high-altitude orbits. This permits the use of commercially available or even consumer electronic components, which are not radiation hardened, considerably reducing subsystem costs.

The third factor is that the nanosat mass range and limited power capability actually drive mission planners to adopt "single-string" (non-redundant) designs that reduce overall system complexity and testing requirements. This often enables even further cost reductions.

Thus, the economic advantages of cubesats rest with the growing capability of microelectronics, with the speed with which a cubesat can be designed, built, and launched, and with those factors that scale with size and/or mass. They are highly beneficial to university research, and they enable graduate students to fly experiments in space during their comparatively short educational careers. Cubesats are also ideal for high-risk/high-reward experiments, where a small investment can test research ideas that otherwise might consume a large budget, take many years, and never get the funding approvals because of the lower probability of success than competing projects.

Remote sensing cubesats are interesting from an economic perspective because remote sensing is a rapidly growing commercial space application that, in some of its needs, is cubesat-compatible. If these or other cubesats successfully demonstrate the ability to deliver competitive commercially valuable information, there is the possibility of a future economic market for their products.

With all of the above examples, cubesats must eventually prove that their benefits outweigh their costs. Rigorous economic analysis would look at the cubesats in a business case scenario. Is the investment in the cubesat more advantageous than using those funds in alternative uses? An example will clearly illustrate this. If an emerging space-faring nation wishes to develop a cubesat that will provide information about the use of land in that nation (through remote sensing technologies), should the nation invest in the development of the cubesat, or should the nation simply purchase similar data from an existing commercial satellite operator, assuming that the cost of the commercial data is less than developing one's own system?

If it were less expensive to purchase the data, a strict economic cost/benefit analysis would suggest not developing the cubesat. However, the unquantifiable components of the decision might lead to the opposite conclusion. These components include the education value to the indigenous scientists and engineers, the national pride in owning a space asset, the security of having one's own private and specialized data source, and the development of a potential product to market to others and recoup some of the costs of the satellite.

Other considerations such as "cluttering" space with many small objects that would require sophisticated orbit analysis to avoid interfering with larger operating satellites, and insuring de-orbiting of the cubesat when their missions are over must also be evaluated. In addition, adhering to legal and regulatory requirements such as registering them as space objects, recognizing potential liability issues, and meeting safety and spectrum-usage limitations will also impact economic and policy decisions, particularly when there are many cubesats simultaneously in low-Earth orbits.

While cubesats offer a new, faster, and less expensive way of putting some scientific experiments and some other space capabilities into operation, the economic and policy questions that will determine whether cubesat technologies become a standard for space exploration, or develop into an interesting and very useful niche market, will remain unanswered until this capability matures and design, launch, and ground-support systems are standardized. The long-term cost functions will then enable users of cubesats to accurately compare this choice of getting to space with other methods of accomplishing the same or similar operational goals.

## 6. Future perspectives

### 6.1. Contemporary issues

Some of the most pressing issues that impact current cubesat stakeholders and entry of non-traditional actors into the community of space-technology-savvy countries are lack of flight opportunities, space situational awareness (SSA), and standardization.

Access to space, specifically increasing the number and frequency of secondary payload opportunities, is a dominant issue for all cubesat space actors, both cubesat veterans and new entrants. As discussed previously, there are signs traditional microeconomic dynamics are beginning to drive the price structures and operations of space launch providers. Most launch providers have incorporated or plan to accommodate secondary payloads, owing significantly to the cubesat and P-POD standards. This trend should continue, provided current and new space cubesat actors continue to support standards.

SSA in the context of space debris is an issue previously mentioned. Technological solutions and procedures that responsibly de-orbit end-of-life cubesats address only part of the issue. New actors that choose to enter the community of space-capable countries through the opportunities provided by cubesats increase the population of satellites in LEO, particularly in the sun-synchronous belt which in turn adds pressure on SSA for all space actors with assets in LEO. Hence, new actors must also commit to engage with the space community on addressing SSA. Adherence to the UN space object registration convention (UN Convention on Registration, 1976), data sharing of spacecraft ephemeris, supporting "rules of the road", and other confidence-building measures are all topics current space actors are contemplating to ensure the global commons of space remains sustainable.

Standardization to a common form factor and adoption of modularized internal components contributes to the general success of cubesats: redesign of the structural bus for each mission is eliminated, and more consolidated markets for commercial component suppliers are created, both of which reduce development times and lower costs. A standardized form factor and mass range made the P-POD and related standard deployment mechanisms viable (Section 2.1). All the above factors result in increased numbers of flight opportunities—as secondary payloads and through ride sharing. Following standardization of launch interfaces and deployment procedures, launch-service providers have developed a level of familiarity and comfort with the cubesat specification and the P-POD deployer. To depart from these standards may marginalize hard-fought gains the small satellite community has achieved for space access.

### 6.2. Technology and innovation

The ability to deploy entire constellations based on cubesats has potential applications in the sciences and remote sensing. As the payload capabilities improve and the tolerances for formation flying and attitude control improve, it may be feasible to apply interferometric methods in place of reliance on monolithic platforms (Martin and Kilberg, 2001; Yang Zhen Ruliang, 2002). There is precedent for interferometric methods in terrestrial-based radio astronomy such as the Allen Telescope Array (ATA). QB50 is a proposed international cooperative initiative that will deploy over fifty cubesats to conduct *in situ* measurements of the lower thermosphere (between 90 and 320 km) and analyze re-entry effects (QB50, 2010). The challenges for such methods applied on orbit are numerous and substantial, but the benefits make it worthwhile to find solutions to these challenges.

Cubesats launched on ISS servicing missions could be deployed as co-orbiters with the ISS. Upon completion of the mission, the cubesat could be tele-robotically retrieved for payload return as provided in NASA's Commercial Orbital Transportation Services (COTS) down-mass process. The cubesats would be managed akin to free-flyers as envisioned for the ISS. This operational mode would provide opportunities for return of products processed by payloads and samples from the space environment without the need for developing capsule return systems on cubesats.

Assuming the cubesat standard remains largely unchanged for the medium time horizon (5–10 years), increased utility will have to come from innovative configurations and continued reliance on miniaturization of hardware. Extending the miniaturization strategy to the nanoscale may even impact this process.

### 6.3. International collaboration

Cubesats offer countries with burgeoning or maturing space technology programs multiple opportunities to collaborate with international partners. One model for cooperation might be scientific data sharing in exchange for rideshare opportunities. Cubesat programs can be a vehicle for technical exchange and multi-lateral cooperation. An example that has taken root in South and Central America is the Robotics Institute of Yucatán (TRIY), Mexico. TRIY, the Pontificia Universidad Catolica of Peru, and the Sergio Arboleda University of Colombia are pursuing cooperative projects, an example of which is a dedicated cubesat Earth station with a 21-m antenna. The Sergio Arboleda University in Colombia is working cooperatively with other participating institutions of TRIY to develop the TRIY-Sat cubesat to demonstrate 3-axis stabilization, a key requirement for remote sensing (TRIY, 2010).

Another option that is especially suited for academic institutions is to provide ground station services. A university department can either become an independent provider of tracking and downlink/uplink services or become a node in international networks such as GENSO or UNISEC GSN-WG. As discussed previously, barriers to entry are very low but the return on education, experience, and collaborative relationships gained can be invaluable. Sharing data from cubesat experiments and working in a joint effort to guarantee launch access and worldwide ground operations coverage will secure a sustainable cubesat program with many players.

### 6.4. Small Satellite activities in developing nations

Adoption of nanosatellite and cubesat technology by nations with developing economies is not just a future vision, it is an emerging reality, with a significant list of activities already under way, a number of which are described here.

Multiple nations are active in small satellites in Latin America. Argentina launched the 6-kg Pehuensat-1 in 2007 into a 640-km polar orbit (Pehuensat, 2010). Still functional, Pehuensat-1's educational mission is to enable students to broadcast messages in Spanish, Hindi, and English (AATE, 2010). Brazil has embarked on development of its first cubesat, the 1U NanosatC-BR, which will use a magnetometer to study the geomagnetic field in the region of the South Atlantic Magnetic Anomaly and the equatorial electrojet over northern Brazil (Savian et al., 2009). Colombia's first space mission (see Section 3), the Libertad-1 cubesat, is an entry-level technology familiarization mission with a mission lifetime of about one month (Libertad-1, 2010).

Mexico has steadily developed capacity in satellite technology starting with its SATEX small satellite program, initiated in 1984. Now in the late stages of development, the 47.5-kg SATEX-1 will test atmospheric attenuation of optical uplinks using a ground-based cooperative laser beacon (Pacheco et al., 2002). In addition, a consortium of Mexican universities is participating in the UN HUMSAT project through development of SATEX-2 (Aguado and Vilan, 2010), and the University of Mexico is collaborating with a number of Russian institutions to develop UNAMSAT-3, a 10-kg nanosatellite that will attempt space-based earthquake prediction by studying ionospheric precursors (Pulinets et al., 2006).

Peru aspires to its first satellite, Chasqui-I, a cubesat in development by the Universidad Nacional de Ingeniería. With its remote sensing payload, the goal of the Chasqui-1 project is to enhance Peruvian space technology capacity and encourage international collaboration (Chasqui-1, 2010). The Chasqui-1 team includes faculty and student collaborators from the US and Taiwan and it utilizes social networking tools for public outreach, including Twitter, Facebook, and YouTube (UNI, 2009).

Activity in Eastern and Southern Europe includes Croatia's upcoming launch of its first satellite, the CROPSAT cubesat, to conduct upper atmospheric research and for space technology capacity building (CROPSAT, 2010). Turkey has successfully launched its first native satellite, the ITUpSAT 1 cubesat, operating now for nearly a year, with a primary mission of education and aerospace technology development (ITUpSAT 1, 2010). Romania will join the family of space faring nations with the launch of the cubesat Goliat on the European VEGA launcher. Goliat primary mission is education and workforce development but also has science payloads including a micrometeroid detector and sophisticated Earth imaging camera (ROSA, 2010).

In South Asia, India, a staple provider of space access opportunities for cubesats through its PSLV rockets, launched its first indigenous picosatellite, STUDsat, in July 2010. Developed exclusively by undergraduates from seven Indian academic institutions, STUDsat's primary mission is education; it includes a camera with stated lateral resolution of 90 m for Earth imaging (STUDsat, 2010). One of at least two cubesats under development in Pakistan, ICUBE-1 from the Institute of Space Technology is an education-and-training project to develop space technology capacity (ICUBE-1, 2010).

Activity in Africa includes Tunisia's development of its first picosatellite, ENIS REGIM pico satellite 1. ERPSat-1 has three basic missions: ground station communication, inter-satellite communication, and remote sensing using a low-resolution CMOS camera (Neji et al., 2009). South Africa is following the successful development of the small satellites SunSat (launch: 1999) (SunSpace, 2009), and SumbandilaSat (launch: 2009) (CSIR, 2010), as well as its contribution of a small satellite bus to the India/Brazil South Africa Dialogue Forum (IBSA) Satellite Programme (Berri and Ruchita, 2008), and a 3U cubesat led by the Cape Peninsula University of Technology, French South African Technical Institute. The 3U cubesat will have three payloads including a camera, a repeater/transponder to rebroadcast messages from amateur radio operators, and a high-frequency beacon to assist the Hermanus Magnetic Observatory in the calibration of its radars in the Antarctic (F'SATI, 2010; Space and Beyond Digest, 2010).

## 7. Conclusions

Cubesat development programs mirror the multi-disciplinary nature of traditional satellite development but at a fraction of the cost and time. We have reviewed the current cubesat evolution concerning configurations, technologies, and current operational constraints. The current status of launch providers, ground stations, and deployment systems as well as propulsion, de-orbit systems, and communications were described. We highlighted the rapidly evolving maturity of the cubesat as a science platform. Further, we discussed implications for STEM education and technology innovation as well as economic rationales. We addressed future perspectives and the role cubesat programs can play in international collaborations.

As small-satellite technologies begin to facilitate bona fide science experiments, their comparatively low cost and the ubiquitous opportunities to deliver them to space will make possible something that has been woefully lacking in space science to date: replicate experiments across multiple space flights. Emerging and developing countries have an opportunity to realize the tremendous potential for workforce and indigenous technology development and a venue for citizen outreach enhancing pride in national science and technology prowess.

The cubesat has the potential to become the “satellites for the people”: aerospace technology for the masses. Policy makers should promote the benefits cubesats offer to STEM education, science research, and potential economic spill-over effects. Cubesats are able to capitalize on the latest technology to fly instruments that truly are “state of the art” and can address the latest high priority issues.

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