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CubeSat Confusion: Technical and Regulatory Considerations

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Summary

Success in space flight operations is often difficult due to the harsh space environment. Naturally occurring charged particles and other cosmic radiation cause short- and long-term issues with onboard electronics and mechanical mechanisms; extensive amounts of UV light degrade satellite surface treatments; and the extremes of heat and cold challenge satellite designs. Additionally, self-induced issues involving design, construction, testing, launching, and monitoring can result in premature satellite failures, so the odds are stacked against full mission success for many resource-constrained space missions. Of particular concern is the growing number of very small satellites (CubeSats) launched en masse that for a variety of reasons are never identified or brought online because of early on-orbit failure. As the number of massed CubeSat launches rises, and the number of CubeSats per launch increases due to flight opportunities brought about by launch consolidators, the number of CubeSats deployed that are "dead on arrival" (DOA) increases. Beyond the heartbreak this brings to the owner/operator teams, DOA CubeSats violate guidelines and best practices designed to decrease the amount of space debris in orbit.[1] This paper investigates the detailed nature of this rather paradoxical problem, in which the inability to identify (ID) a satellite may cause its early demise and a non-functioning CubeSat may be difficult to ID, adding to the confusion. To mitigate this problem, the paper will examine a number of regulatory, systems engineering, and technical solutions involving low-cost means to facilitate identification of CubeSats after launch along with planned flight demonstrations of some of these techniques and technologies. The desired outcome is to outline a practical means to independently identify space objects.

Introduction

CubeSats, small satellites built around a 10 cm building block (i.e., a one unit or "1U" CubeSat is 10 cm x 10 cm x 10 cm, a 2U is 20 cm x 10 cm x 10 cm, etc.), offer affordable access to space. Their standardized size and shape have allowed a CubeSat industrial ecosystem to flourish, which has lowered costs for acquisition and launch, and vastly shortened development times. This has enabled access to space for many nontraditional actors in the space arena beyond deep-pocketed governments and companies. What previously might have taken years to develop can now be accomplished in months, and for significantly less money. This has allowed educational institutions, down to the middle school level, to fly their own CubeSats. It has also allowed numerous developing countries their first satellite. It has allowed more traditional aerospace companies and government agencies very rapid cycle times for research and development efforts. In short, it has opened up outer space to many more than in the first half-century of the Space Age. Yet it is those same beneficial characteristics (small, uniform size and shape, low cost for acquisition and launch, etc.) that have led to a complex technical challenge that is rather unique to CubeSats. This work addresses this challenge and explores various solutions: systems engineering techniques, technical solutions for independently identifying space objects[2], and regulatory and policy issues.

It is certainly in no one's interest to launch satellites that are dead on arrival to orbit, die shortly after launch, or cannot be identified and connected to ground support. Internationally agreed to guidelines suggest minimizing the launching of debris[3]; additionally, when an object is launched into space, it is the responsibility of the Launching State, the State overseeing and supervising the launch, to register the space object.[4]

If a satellite cannot be identified, it is often very difficult to establish ground-to-space radio communications. This is because the satellite typically has a weak radio signal, and with a narrow-beam ground-station antenna, it can be hard to efficiently search for it.[5] If there are numerous unidentified satellites from the same launch (e.g., a swarm of CubeSats), the owner/operator can try to establish communications with each satellite in turn, but they are often in close proximity. With only a few brief passes available to connect with a ground station, successful contact might not be established. This makes it extremely difficult to establish communications and perform early-orbit operations vital to the survivability of the satellite.[6,7] In some instances, an operator may point the ground station antenna at a "bunch" of satellites. If they are close enough to each other, the operator might get lucky and communicate blindly with the correct satellite. However, luck should not be a strategy. Extensive searching consumes time and resources. During this time, the satellite might fail before it is identified, perhaps because of an electronic circuit latch-up or due to battery discharge.[8]

This sets up a hazardous paradox wherein:

- Unidentified satellites cannot be correctly noted in catalogs of space objects.[9,10]
- Owner/operators cannot be notified of any conjunction assessments (although given that many CubeSats do now have maneuver capability, this may not be the most important consideration).
- Unidentified satellites cannot be registered with the United Nations Office of Outer Space Affairs (UNOOSA), thereby impeding a Launching State from fulfilling Outer Space Treaty obligations.[11]

How Did We Get to This Situation?

At the start of the Space Age (1950s and early 1960s), satellites were small (e.g., Sputnik and Explorer).[12] However, over the decades, more capable launch vehicles enabled satellites to increase in size, mass, and power and fulfill increasingly challenging scientific, commercial, and defense missions. The price to launch into orbit (dollars per kilogram to orbit) favored the use of large, expensive launch vehicles.[13] Launching a small payload on a dedicated rocket was usually not viable or efficient because of the discrepancy between the launch vehicle lift capability and the satellite size and mass. In this case, the cost of the large rocket would eclipse the cost of the satellite. When small payloads did need a ride to orbit, they generally went along as a secondary payload. This is how early CubeSats got to space. Small satellites as secondary payloads were sometimes "dropped off" along the way to the primary payload's orbit or they rode along to the final orbit position with the primary payload. In either case, it usually was not difficult to distinguish between primary and secondary payloads via size and operational parameters.

The situation changed as consolidators began bundling CubeSats and other smaller payloads together with larger payloads.[14,15,16] Ride sharing helped fill the excess capacity of many launch vehicles and enabled more cost-effective launches for small satellites. Eventually, consolidators began buying up entire launch vehicle manifests, and reselling the ride to a large number of CubeSats. In these cases, there was no longer a primary, large payload, as the entire capacity was filled with small satellites. As microsatellite size envelopes became standardized with the advent of CubeSats, a berth on a rocket became fungible[17]; if any given CubeSat with a reservation on a launch manifest fell behind schedule, that reservation could be traded to a CubeSat that was ready to go. CubeSats enabled an economy of scale, both for production and for launch, which further decreased total mission costs.

Thus, we now have the situation where various capable launch vehicles (such as SpaceX, Rocket Labs, Polar Satellite Launch Vehicle (PSLV)) are manifested solely with large numbers of CubeSats coordinated by consolidators.[18,19,20] For technical and cost reasons, the CubeSats are generally launched into very similar orbits over a short time period. Such batch launches are what gave rise to "CubeSat confusion." By launching CubeSats with low spatial separation, they become hard to distinguish from each other. By launching them with low temporal separation, existing space situational awareness (SSA)/space traffic management (STM) systems[21] do not have time to react to the addition of so many new space objects all at once.[22,23,24] As Figure 1 shows, it can take weeks or months to identify objects (and some may never be uniquely identified at all).[25] Note that this scenario is not generally realized for launches consisting mainly of one company's satellites (e.g, SpaceX StarLink or Planet constellations) because the company will have the ability to communicate with their own satellites, can determine via telemetry the identification (ID) of each one, and generally have an established relationship with SSA/STM systems that can help resolve discrepancies in identifying their satellites. Additionally, large batches of commercial satellites launched in constellations are fully functional production class rather than experimental satellites with limited capabilities.

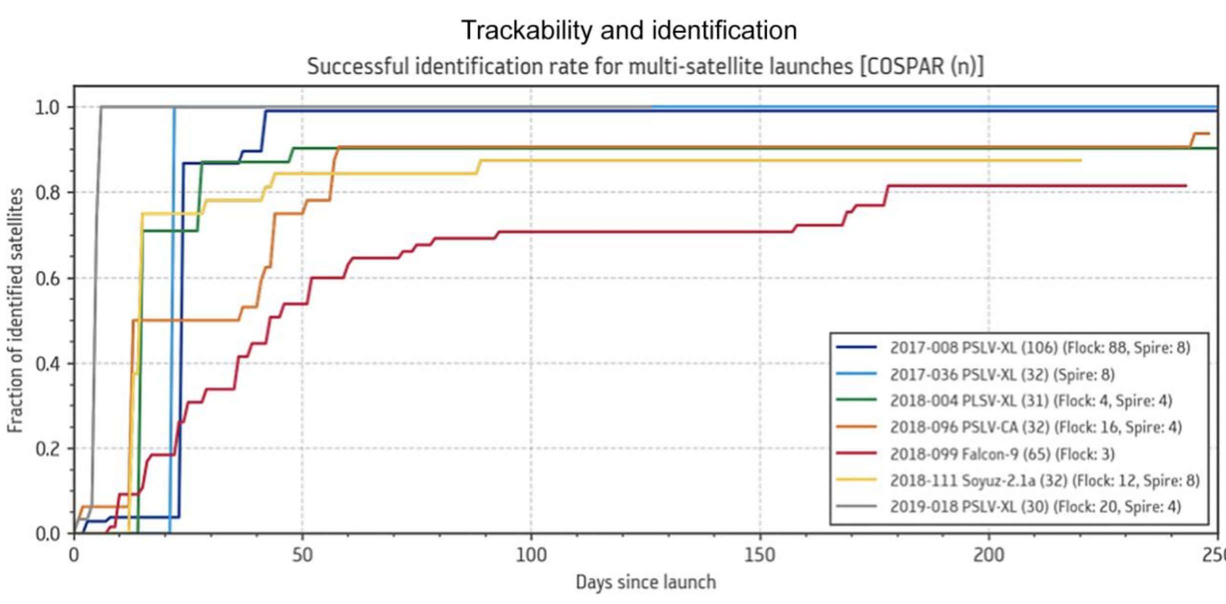

Figure 1: It can take weeks to months to identify most of the object launches, and in some cases 10 percent to 20 percent may never be identified, even after six months or more. Image used with permission of ESA.

So, What's the Issue?

Because of their standardized shape and size, CubeSats look very similar to one another, especially when they are on-orbit hundreds of kilometers away. If there are unidentified objects from a launch, then the possible number of associations of object ID to tracked object scales as $n!$ (n-factorial[26], where n is the number of unidentified space objects from the launch). For example, if there are just two objects, say a payload and an upper stage, there are two ways in which you can associate the IDs with the tracked objects, and even that can be a challenge.[27] However, if there are 10 unidentified objects, there are 3,628,800 possible combinations; with 20, this rises to 2.4 quintillion combinations. The magnitude of the problem grows rapidly. Figure 1 shows how well recent CubeSat launches did at identifying all of the objects launched.

The features of CubeSats that have made them so attractive to the educational community, and others doing rapid technology development missions, have also at times endowed them with low reliability:

- The use of commercial off-the-shelf (COTS) and other low-cost, non-radiation-hardened parts can lead to early on-orbit failure (and many CubeSats do not use radiation-hardened electronic components).
- The small form-factor of CubeSats often precludes the addition of redundant systems.
- Their rapid development may mean a lack of backdoors and other workarounds to reset a CubeSat that has locked up on orbit.
- Their small size can also make them hard to work on, access being an issue, and working on their interiors may cause damage from handling.
- Because of limited budgets and compressed timelines, as well as lack of available and affordable facilities, system and sub-system testing is generally limited.[28] Lurking issues may not be discovered and resolved before launch (when they could be remedied).

These aspects can lead to early on-orbit electronic component latch-ups due to the harsh radiation environment (from passage through the South Atlantic Anomaly (SAA), for example).[29] Without a self-healing ability or other fail-safe design elements, recovering from on-orbit failures is extremely difficult, if not impossible. Statistics on CubeSat mission success rates indicate that 27% of CubeSats launched since 2000 (excluding commercial constellations of CubeSats) are either DOA or die shortly after launch.[30] As the success rate for nonprofessional CubeSat builders does not seem to be improving, and as more CubeSats are launched, more of them will be nonfunctional soon after launch, and a larger number will remain unidentified.[31] A failed CubeSat that has yet to be identified on-orbit will most likely never be claimed, especially if it has no independent means of identification. The problem is made worse when the CubeSat is part of a rapid deployment of scores of similar CubeSats into nearly identical orbits, which limits the ability of existing SSA/STM systems to react to the increased population of new space objects.

"A failed CubeSat that has yet to be identified will most likely never be claimed."

What Set of Solutions Can Be Advised to Mitigate This Issue?

In keeping with the low-cost and rapid development cycle for CubeSat missions, solutions will be considered that:

- Fit within the CubeSat paradigm.[32,33,34]

- Stay within the envelopes of a CubeSat's size, weight, and power (SWAP).
- Offer low cost to the mission.

However, there is no free lunch, and any proposed solutions will have some impact on the cradle-to-grave mission timeline. While it is in no one's interest to have multiple unclaimed CubeSats that are dead on arrival, there is no new panacea that will solve the problem.

A multi-faceted approach of systems engineering, design, technical best practices, and regulatory/ policy solutions can help improve CubeSat challenges. Various practices are described below.

Improve Reliability Components and Communications

To avoid launching space debris, it is important to take steps to improve reliability and mission success. If the mission resources do not allow for radiation-hardened electronic components or redundant systems, mission designers should consider building in fail-safe design elements that allow the mission to recover from early orbit component failures and latch-ups. A detailed inventory of such design elements is beyond the scope of this work, but a few examples of these best practices would include the use of watchdog timers[35] to allow automatic recovery from latch-ups, as well as the inclusion of alternate means by which the CubeSat mission team can communicate with their CubeSat by incorporating a low Earth orbit (LEO) communication satellite network radio (e.g., GlobalStar or Iridium).[36] These radios are typically credit card size, are within the budget of a typical CubeSat mission, and can offer low bandwidth, bidirectional communication at arbitrary satellite locations, not just when the satellite is in range of the mission's ground station.

Coordination, Collaboration, and Transparency

Enhanced coordination, collaboration, and transparency (i.e., sharing of plans and other mission-important information) between the CubeSat owner/operators, the launch provider, and the relevant SSA/STM center is another CubeSat-friendly systems engineering consideration that should be implemented during mission development.[37,38] Coordination should begin well before launch (months to years), and should include the expected deployment order, the launch vehicle sequence of events, and the creation of early orbit determination contingency procedures. The coordination plan should establish relevant points of contact (POC) as well as communications mechanisms and links between all concerned. These should be updated as necessary, and as the launch date approaches, there should be a communications rehearsal.

After launch, the communications network should be open and active for the first several days or weeks between all the parties. The groups should monitor and share orbital information as it becomes available to guard against cross-tagging (misidentifying) any of the CubeSats. It is also important that the operators be informed regarding the limitations of the SSA/STM system, and that the launch provider makes prelaunch orbital data and postlaunch updates available for each of their CubeSats, to be shared with their customers (the CubeSat operators) and the SSA/STM data providers.

Shared Information and Interoperability

Everything being deployed from the launch vehicle must be accounted for (not just the CubeSats), and information must be shared in clearly defined, consistent formats, reference frames, and units that remain fixed. Furthermore, the orbital information being shared between the launch provider and the operators should be interoperable with the SSA/STM providers, and operators should communicate with the SSA/STM providers when they find their object and communicate with it. Operators may also want to engage an independent tracking service, which may be of help in locating satellites and providing updated orbital information. The CubeSat deployer may wish to consider using automated tools to assist in the matching of objects with the various orbits.

Deployment Tempo

The method by which CubeSats are deployed from the dispenser on-orbit is another concern. One simple idea is to stagger and spread out the launches in time, allowing a revolution or two around Earth between launching pairs of CubeSats to afford the SSA/STM systems time to react to the new objects on orbit. Some issues with this approach are the locations and availability of relevant ground stations. Also, there are some worries regarding latch-ups from the first SAA passage.

Deployment Method

Consideration may also be given to how the CubeSats are deployed from their dispenser. Braun and Herrin, with experience from their involvement with the Operationally Responsive Space 3 (ORS-3) mission, point out that the orientation of the CubeSat dispenser is quite important.[39] To avoid imparting a torque on the dispenser causing unwanted rotation, CubeSats are normally deployed in pairs, in opposite directions. But if that direction is in the radial or cross-track direction, the CubeSats will return to their starting location and "bunch up" after each orbit, and it will be hard to segregate the CubeSats by location. However, due to orbital mechanics, if the satellites are dispensed in the forward or reverse of the along-track direction, those launched in the forward direction will move to a higher orbit and will tend to lag the dispenser while those launched in the reverse direction will move to a lower orbit and will lead the dispenser. The net effect is that the CubeSats will spread out, in a "string of pearls" (see Figure 2), and it may be possible to differentiate between them. Additionally, it is helpful to take the area-to-mass ratio of the CubeSats into account, and to help spread things out, the lighter, higher area-to-mass ratio CubeSats should be deployed first.

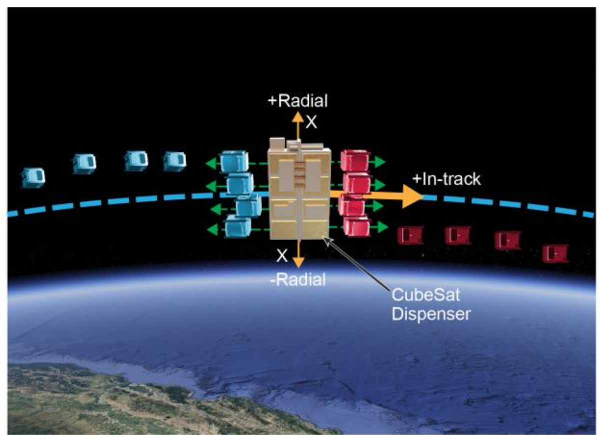

Figure 2: Note the "string of pearls" above and below dispenser altitude achieved by deploying pairs of CubeSats in the +/- in-track direction. Deploying along a radial and cross-track would lead to "bunching," which causes confusion, cross-tagging, and misidentification.

Identification Schemes

Practical considerations and wise planning call for CubeSat owners to make their satellites independently identifiable, should they not be able to open communications links immediately post-launch (or should the CubeSat not function at all). A previous paper described a number of techniques and technologies useful for tracking and identifying small space objects.[40] Here, we discuss a few options, all with fairly high technology readiness levels (TRL), that may be affordable for even lower cost CubeSat missions. The various technologies exploit different schemes, but all of them can operate independently of the functional state of the CubeSat, and all of them can determine not just the unique identification of the CubeSat, but also orbital information. Note that size, weight, and cost vary for each of the examples, but all can be considered compatible with a CubeSat mission (consult references for information on SWAP and cost). These devices are described in Table 1.

Scheme 1, a PNT receiver is paired with a small transmit/receive radio with an omni-directional antenna

- PNT signals are received by the CubeSat and position (x, y, z) and time are determined for the CubeSat.
- These data are transmitted to a commercial ground station over a LEO commercial communications constellation (e.g., Global Star or Iridium) and relayed to the satellite owner via email in near real time (Figure 3).
- The PNT receiver and radio can be configured to be mounted on the exterior of the CubeSat with their own power source (solar panel and battery). The PNT and radio thus function independently of the CubeSat and will work even if the CubeSat is non-functioning on-orbit.
- Other data can be configured to be radioed to the owner (e.g., tumble rate, received radiation dose, or satellite health and status information).
- It is possible to integrate these devices even further into the command and data handling subsystem of the CubeSat, allowing an alternate path by which the satellite owner can upload commands to the satellite even in the absence of normal ground station contact.
- Voss describes commercially available examples of these devices, with flight heritage, that are sized to fit on the exterior or interior of even a 1U CubeSat, with a mass of about 120 grams.[41,42]

Scheme 2, a small light source and power supply, mounted to the exterior of the CubeSat

- The light source is modulated in a unique pattern of *on* and *off* signals and is detected via a ground-based telescope (Figure 4).
- The light sources are too faint to allow blind searching of the sky for the satellite; orbital information from an SSA/STM provider will be required to find and track the CubeSat.
- However, in tracking the satellite while receiving the coded signal, the orbital information can be refreshed by the tracking telescope.

Scheme 3, a small RFID tag (or tags) affixed to the outside of the CubeSat

- A coded signal is received when the tag passes through a beam of radio frequency energy with the appropriate wavelength, as seen in Figure 5; i.e., the tag is designed to be read by a radar of a certain frequency (e.g., X-band), and will return an ID for X-band radars, but not for other radars (e.g., S-band).[43,44]
- A traditional Van Atta array, in which power is delivered to the array via the radar beam, does not require an internal energy source. The array serves only to enhance the radar cross section of the CubeSat.
- The RFID tag does require a small amount of power, provided by a small amount of solar cell material, to return a unique ID number. Orbit information on the object is updated when it passes through the radar beam.
- This scheme works day or night and is generally immune to bad weather on the ground.

Table 1: Various Technology Schemes Considered for Inclusion in a Space Test to Identify Cooperative CubeSats			
Technology Scheme	**Description and High TRL Example**	**Advantages**	**Disadvantages**
CubeSat Position and ID Via Radio	A position, navigation, and timing (PNT) receiver is attached to a CubeSat, along with a radio to transmit the information via a LEO communications provider; example product: NearSpace Launch *BlackBox*	Can provide ID and meter-level positional uncertainty in near real-time, independent of state of health of the CubeSat. Accelerometer can also indicate if tumbling.	Current offering list price of $13,500 may be unaffordable for some missions.[45] Needs owner/operator to acquire FCC license.
Coded Light Signals from Light Source on Exterior of CubeSat	Exterior-mounted LEDs using larger aperture telescope to receive (University of Michigan *LEDSat*[46]) or diffused LED laser using ground-based photon-counting camera (LANL *ELROI*[47])	Lightweight and inexpensive. The act of tracking with ground-based telescope provides orbit update.	Lower TRL, not available as an off-the-shelf product or service. Limited to clear nighttime terminator conditions.
Radio Frequency Interrogation of an Exterior Van Atta Array	Exterior mounted radio frequency identification (RFID) tag and commensurate radar (SRI *CUBIT*[48])	Lightweight, low cost, independent power. Unique ID, orbit updated during tracking.	Not yet available as a COTS product or service. Only works with specific radars.
Laser Interrogated Corner Cube Reflectors (CCR)	One or several small CCRs can be attached to CubeSat exterior; ground-based laser and receiver telescope needed to distinguish number of CCRs.[49]	Low SWAP can provide cm-m level positional uncertainty. Independent of satellite state of health.	Limited by number of CCRs that can be attached. Ability to lase may be limited by payload. Not currently a COTS service.

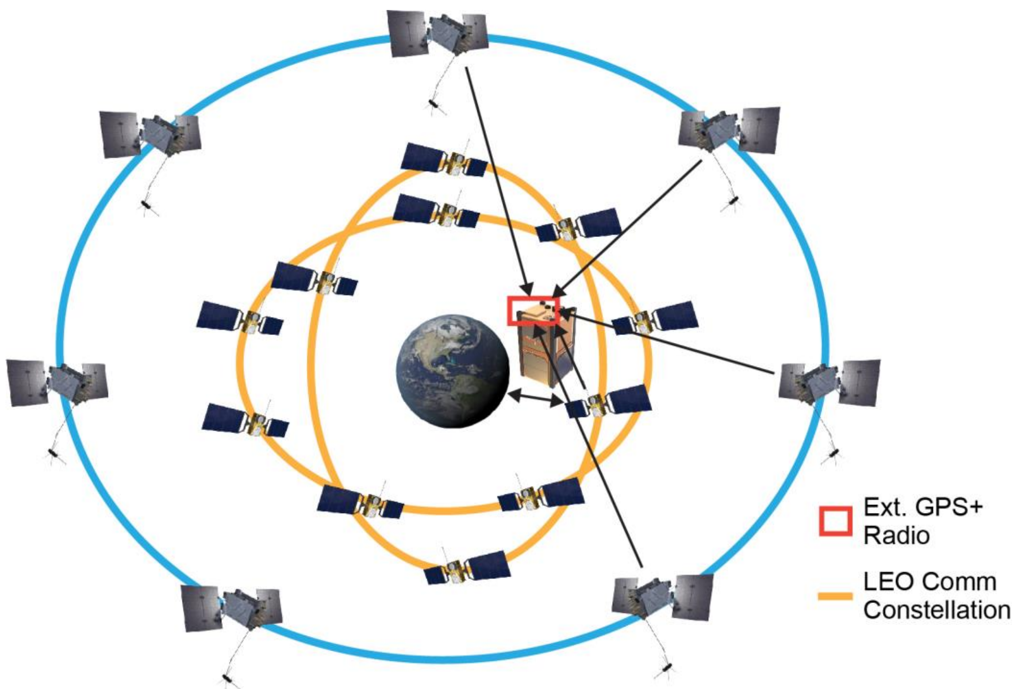

Figure 3: The PNT-derived coordinates of the CubeSat ((x,y,z,t) + ID) might be radioed down via a low-bandwidth LEO communications constellation. (Not to scale)

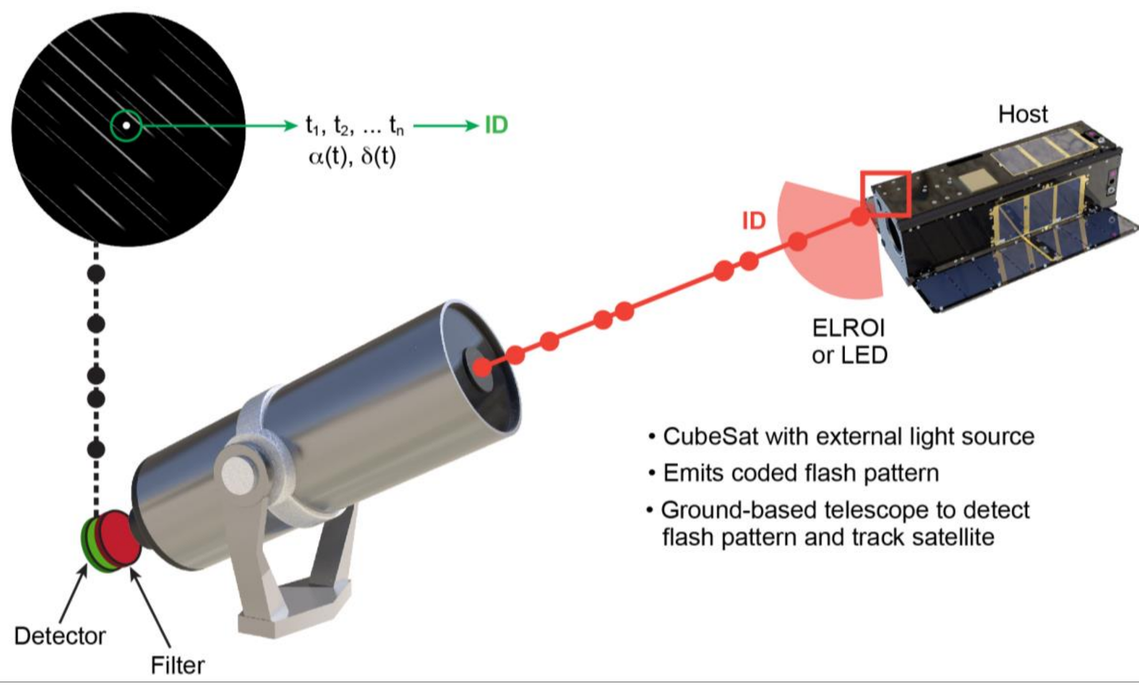

Figure 4: Displays a scheme with a CubeSat outfitted with an external light source, one with a distinct flash pattern, being detected and identified by a ground-based optical telescope.

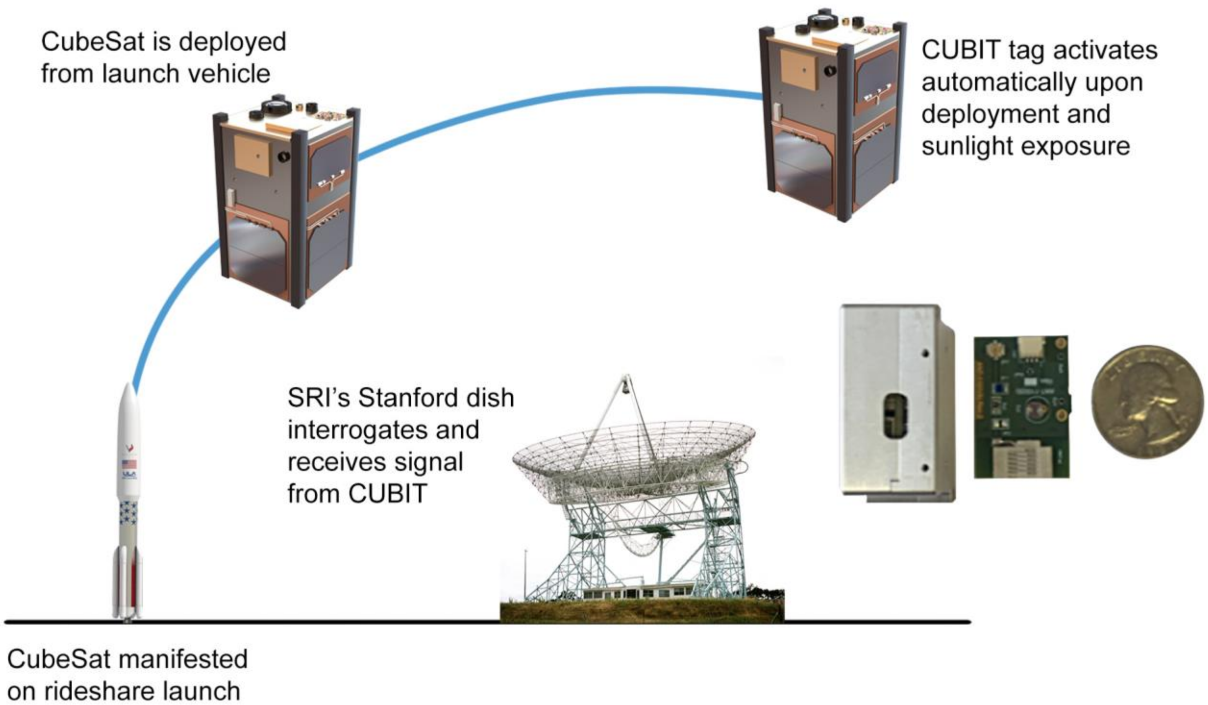

Figure 5: Displays SRI's CUBIT RFID scheme; the inset shows a photograph of the CUBIT RFID tag. (Image used with permission.)

Scheme 4, very low-SWAP and cost technology with a high TRL level, the corner cube reflector (CCR)

- Such devices are available commercially for low cost.
- CCRs are just a special mirror designed to reflect laser light back in the direction from which it arrived.
- They require no internal energy source.
- When illuminated by a laser, they provide a return signal that can be detected on the ground by a fast camera, as seen in Figure 6.
- Putting a different number of CCRs on a set of CubeSats allows the ground station to differentiate between the CubeSats (i.e., a CubeSat with one CCR will produce a different return signal from another with a two CCRs or three CCRs).
- One can use a laser and telescope system like those employed by the International Laser Ranging Service (ILRS)[50], which are high TRL and have been operating for decades.
- Precise orbital information is required to lase the CubeSat and receive a return signal.
- Because the laser provides a strong signal, the satellite being tracked does not need to be sunlit.
- ILRS-tracked objects with CCRs can have their orbital positions determined to the sub-meter level.

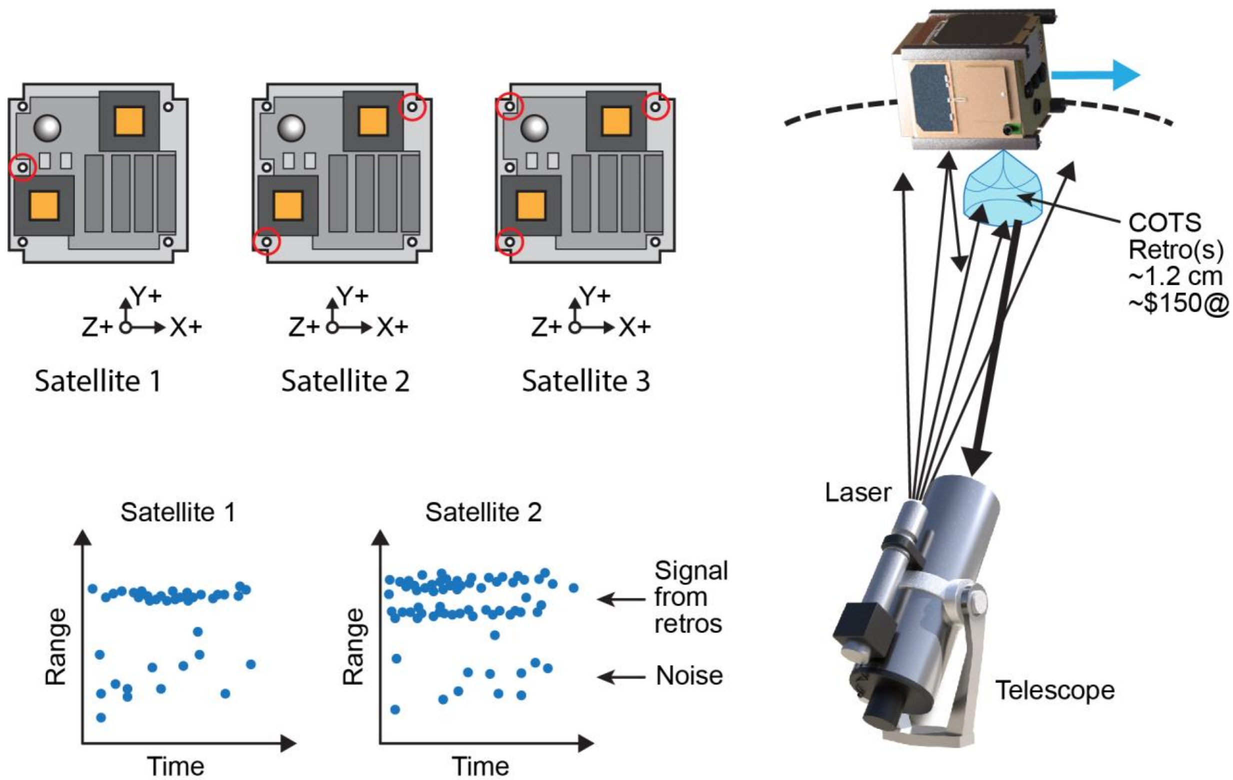

Figure 6: Displays a scheme to outfit CubeSats with small COTS retroreflectors. By varying the number of retros on the face of a CubeSat, different returns are observed when illuminated with a ground-based laser and observed with a co-located telescope.

- The small cross-sectional areas of CubeSats will limit the maximum number of CCRs that may be affixed to "several."

CubeSat Regulatory Landscape

How are CubeSats Regulated?

Regulation of outer space activities has almost always lagged behind the development of space technologies, and CubeSats are no different in this regard. A regulatory regime that addresses some of the issues of CubeSat confusion can help assure a sustainable space environment for all users. But how to get there? The development, testing, validation, and demonstration of techniques and technical solutions to CubeSat confusion can directly inform not just owner/operators, but also regulators. "Industry Day" discussion fora and technical demonstrations can illuminate the problem set and viable solutions, and the lessons learned can be incorporated into a variety of mechanisms, including guidelines, best practices, advisories, and explicit rules and regulations. Understanding the art of the possible will inform the right regulatory balance. The existing regulatory regime for CubeSats, such as it is, is examined in the following section.

The Outer Space Treaty

Article I of the Outer Space Treaty states:

> The exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or

> scientific development, and shall be the province of all mankind.
>
> Outer space, including the moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies.[51]

Thus the treaty does not differentiate between established spacefaring entities and new actors in the space arena, nor upon satellite size, sophistication, or cost. It makes no reference to CubeSats or anything similar. The only difference recognized for governance is between States and non-governmental entities, as stated in Article VI of the treaty, non-governmental entities "shall require authorization and continuing supervision by the appropriate State Party to the Treaty." As was discussed earlier, satellites at the start of the Space Age were small (CubeSat-sized), and as launch capacity developed, economics favored increasingly larger satellites for many activities. It was with the development of a standard size and shape for satellites that the CubeSat revolution took hold.[52] This has led to an increasing number of small, similarly shaped, often less expensive satellites being launched, often owned and operated by less experienced teams. Might it be possible, through regulation and guidance, to encourage the proliferation of CubeSats while also ameliorating some of the negative consequences?

Regulation Through the Space Age

How have CubeSats been regulated? Are there any differences with their regulation and that of larger satellites? Historically, the answer has been "no, there really are no differences," but regulators may be coming to understand that some aspects of CubeSats (and nanosats in general) make them different from larger satellites. As the National Academy of Sciences noted, "There is no CubeSat-specific domestic or international regime that can require CubeSats to be maneuverable, trackable, or deorbited appropriately"; orbital debris mitigation standards that apply to all satellites also apply to CubeSats.[53] In the United States, the regulatory authorities that a commercial, private, or educational space mission would need to navigate would include the Department of Commerce, the Federal Communication Commission, and the Federal Aviation Administration Office of Commercial Space Transportation (FAA/AST), depending on mission.

U.S. Domestic Regulations

Department of Commerce: Remote Sensing

In the United States, commercial remote sensing (observing Earth from outer space) is regulated by the Commercial Remote Sensing Regulatory Affairs Office, which is part of the Department of Commerce. The office does not differentiate based on satellite size, but rather on the imagery that is produced, to balance national security concerns with commercial viability. They do not regulate based on technology, but rather on what is produced, by the functionality of their imaging systems.[54]

Federal Aviation Administration: Launch and Reentry

FAA/AST regulates commercial launches in the U.S. or involving U.S. participants. A reading of the (amended) Commercial Space Launch Act of 1984 reveals no differentiation based on satellite size.[55] The law is chiefly concerned with advancing commercial spaceflight, whether that is a flight containing a single CubeSat, 100 CubeSats, or a very high-throughput geosynchronous commercial satellite.

Federal Communications Commission: Spectrum and Space Debris

One important thing that CubeSats have in common with larger satellites is the need for radio frequency spectrum to control the satellite and to relay data back to Earth. However, access to spectrum is difficult, as all traditional spectrum is in-use, reserved, or requested by others. This leads to a lengthy application and coordination process to secure authorized spectrum use by national (Federal Communications Commission (FCC) in the U.S.) and international (International Telecommunication Union (ITU)) regulators. This lengthy process to acquire the necessary spectrum runs contrary to the needs and philosophy of many CubeSat missions: rapid development and quick deployment, often with a small (by traditional space mission standards) budget. However, the FCC has made some differentiation for satellite users and what type of license for which they apply.

FCC Licensing Options

In 2018, the FCC streamlined its procedures for a subset of commercial license applications (the Part 25 license). Traditionally, Part 25 applications had long processing times and high application fees[56], and this streamlining created

> an alternative, optional application process with part 25 of the Commission's rules for small satellites. This streamlined process would be an addition to, and not replace, the existing processes for satellite authorization under parts 5 (experimental), 25, and 97 (amateur).[57]

The streamlined process was not aimed at CubeSats per se, but rather at smallsats, and had a number of technical requirements that would need to be adhered to, to qualify under this new process. The application fee, at $30,000, might be seen as unreasonably high for many CubeSat missions.

The other application routes available to CubeSats include Part 5 or Part 97, neither of which are specific to CubeSats but are more in line with a CubeSat's typical mission parameters and ownership. Part 97 is not a license for CubeSats, but rather a permit that allows a licensed amateur radio operator (a "ham") to operate a space station (defined as being more than 50 km above the Earth's surface). There are neither application nor ITU recovery fees for this type of license.[58] Amateur radio satellites have been operated in space since 1961, well before the conception of the CubeSat standard, and fit with the rapid deployment/limited functionality of a CubeSat mission, if not its form-factor.[59] Part 97 is not based on size or shape, but rather on a licensed amateur radio operator's status.

Eligibility for a Part 5 experimental license is limited to "experimentation under contractual agreement with the United States Government, and [for] communications essential to a research project."[60] Note that Part 5 spectrum is not limited to satellite use and is shared with many other experimental users.[61] Experimental licenses are granted on a non-interference basis, and they may neither cause interference nor claim protection from interference.[62] Applicants to Part 5, in addition to those applying under Parts 25 or 97, must also submit an orbital debris mitigation plan to the FCC. Applicants for an experimental license must pay a $70 filing fee and must submit a filing to the ITU (as well as pay the ITU cost recovery fees). The license term for a Part 5 license is from two to five years.[63]

Additionally, Part 5 and Part 97 applicants should be aware of and address the following:

- For satellites that will maneuver at altitudes used by inhabitable orbital objects, the applicant should indicate whether any measures have been taken to coordinate operations with the operator of such object.

- Although most small satellites can be expected to burn up entirely upon re-entry, if the satellite is constructed with high melting point materials some components may survive re-entry and present a casualty risk. Satellite designers are urged and expected to follow a "design to demise" approach in choosing materials.[64]

International Regulations

Spectrum Coordination: The ITU

As Allison has noted, the

> ITU's Constitution also extends "equitable access" to the electromagnetic spectrum and associated orbital resources by all countries… [This] general legal framework applies to all satellite operators, no matter whether they are tiny Cubesats or large communications satellites operating in geostationary orbit. However, as small satellites have proliferated, the applicability of some of the elements of these legal regimes and processes that were originally designed for larger geostationary satellites have become increasingly criticized as being overly burdensome and unworkable for the operators of the smallest satellites, particularly for non-commercial entities, with disproportionate impact on developing countries who may be embarking on their first space-faring activities.[65]

Realizing that the existing application and coordination process does not serve the needs of many smaller satellite users, the ITU studied and discussed streamlining the process for small satellite operators, which has traditionally been a "seven-year long process [as] set forth in [radio regulation] Articles 9 and 11."[66] They found that for CubeSat and other short-duration missions, "a modified regulatory procedure for the advance publication, notification and Master Register recording of non-GSO satellite systems with short duration missions may be beneficial for these systems."[67]

Some of the recommendations of the studies for streamlining were adopted at the 2019 World Radio Conference in Sharm el-Sheikh, in Resolution 32: "Regulatory procedures for frequency assignments to non-geostationary-satellite networks or systems identified as short-duration mission not subject to the application of Section II of Article 9."[68]

The criteria necessary to be considered for these streamlined procedures includes being in a non-geostationary orbit, having a mission lifetime of not more than three years, a satellite mass of less than 100 kg., and not more than 10 satellites in the constellation. Additionally, the requested frequency assignments shall not be subject to coordination.[69]

Foreign Regulatory Regime Example: United Kingdom Space Agency

Other nations' regulatory bodies have begun to understand the benefits of CubeSats to their space economies and have begun to adjust their regulatory regimes to take into account the needs of CubeSats. In 2015, the United Kingdom Space Agency (UKSA) started updating its satellite regulatory framework, recognizing that the existing regulations were not well suited to deal with CubeSats. The goal was to "trim much of the unnecessary administration and repetition from the process of obtaining a license whilst retaining enough regulation to effectively discharge the UK government's responsibility under the Outer Space Treaty of 1967."[70] The approach that the UKSA took was to "... evaluate the risk presented to, and posed by, such systems and consider how its regulatory approach might be tailored for Cubesat systems. Recognizing the common aspects of such missions, there is an opportunity for the UK Space Agency to exploit a range of pre-determined technical assessments and associated likely regulatory outcomes for a range of likely Cubesat systems, presented in the form of a traffic light system (GREEN = low risk, AMBER = medium risk—may require further consideration such as evaluation of safety—critical systems, RED = high risk- likely to present unacceptable hazard to operational population which cannot be mitigated cost-effectively)."[71] They took this approach as they recognized that CubeSats offered a number of common elements (satellite bus design, small size and mass, launches into low Earth orbit, and low cost). They made the decision to regulate these missions, and not just offer blanket immunity from regulation, but with the three-tiered process (GREEN/AMBER/RED), depending on mission design and complexity, the chosen launch system, the final orbit, and CubeSat bus characteristics.[72] It is this traffic light system that has enabled CubeSat developers to produce satellite buses that "upon successful mapping to the GREEN rating, [are] able to be certified in a streamlined, harmonized process."[73]

Do These Regulations Address the Problem?

FCC: Moving Towards 'Trackability'?

But what about *CubeSat confusion*? What about the issues this work has addressed? Namely, issues regarding trackability and identification? Recently, the FCC issued a notice of proposed rulemaking, FCC 18-44, that sought to address some of these issues. In this document, the FCC discussed the CubeSat standard and popularity among both commercial and academic users.[74] It took as a given that a 1U CubeSat (or larger) would be adequately trackable, but that "methods for improving tracking of smaller objects, such as reflectors or transponders, these methods may require closer scrutiny and detailed analysis."[75] In its November 2018 NPRM and Order of Reconsideration regarding mitigation of space debris, the FCC again discussed CubeSats and recognized that the "increase in the number of small satellites, for example, has begun to pose some unique tracking and identification challenges." Also, for objects smaller than a 1U CubeSat, it may be necessary "that the applicant provide additional information concerning trackability, which will be reviewed on a case-by-case basis," and whether the tracking would be "active and cooperative (that is, with participation of the operator by emitting signals via transponder or sharing data with other operators) or passive (that is, solely by ground based radar or optical tracking of the object)."[76] Additionally, it sought "comment on whether we should adopt an operational rule requiring NGSO[77] satellite operators to provide certain information to the 18th Space Control Squadron or any successor civilian entity, including, for example information regarding initial deployment, ephemeris, and any planned maneuvers.[78] As an example, communication with the Air Force's 18th Space Control Squadron may be particularly important in the case of a multi-satellite deployment, to assist in the identification of the satellite."[79] The FCC also sought comment on large deployments of CubeSats, "whether we should include in our rules any additional informational requirements regarding such launches," enquiring if there were "mitigation measures that are commonly employed that mitigate such risks, for example through use of powered flight during the deployment phase and/or through phasing of deployment?"[80] The FCC was also interested in post-mission lifetime, recognizing that with

> satellites that are smaller and less expensive to construct and launch, there has been a corresponding trend toward shorter mission lifetimes for NGSO satellites deployed into the LEO region. For example, the anticipated lifetime of a typical "CubeSat" operating in the Earth exploration-satellite service is only one or two years.[81]

Should they then change the 25-year post-mission disposal rule?

While a discussion on the potential need for requiring satellite maneuverability for objects launched to altitudes above ~400 km is beyond the scope of this work, it should be noted that two of the solutions described above (the external GPS module, and the corner cube reflectors) will allow orbit determination to such precision that will greatly shrink the covariances for the objects' orbits.[82] This may greatly reduce the need for such objects to have a maneuver capability.

Furthering the discussion, based on numerous written comments to the November 2018 NPRM regarding space debris, the FCC released an April 2020 report that discussed, inter alia, trackability and identification. Regarding trackability, the Commission decided to maintain its rule that a satellite with a smallest dimension of 10 cm was inherently trackable (in LEO), and for satellites with a dimension smaller than 10 cm,

> applicants will specify the tracking solution and provide some indication of prior successful demonstrated use of the technology or service, either as part of a commercial or government venture… Tracking solutions that have not been well-established or previously demonstrated will be subject to additional scrutiny, and applicants may need to consider a back-up solution in those instances.[83]

However, regarding devices augmenting tracking and identification, the FCC reported that it found "that the provision of position data in addition to standard space situational awareness data, through radio frequency identification tags or other means, may ultimately be a way to support a finding that a spacecraft smaller than 10 cm x 10 cm x 10 cm is trackable, but until the establishment of the commercial data repository, reliance on most alternative technologies does not appear to be readily implementable."[84] Rather than dictate a technical solution, the FCC seeks to allow the satellite operator the choice of how to achieve a solution to the trackability issue. As tracking and identification technologies improve, the FCC would be willing to revisit the issue. Therefore, it may be interested in efforts to develop and demonstrate various tracking and identification technologies.[85] It also discussed active (via emitted signals) and passive (solely ground-based radar or optical) tracking for satellites, which the applicant would need to disclose.[86] Importantly for resolving CubeSat confusion, the FCC requires that "applicants disclose how the operator plans to identify the space station(s) following deployment, for example, how the operator plans to obtain initial telemetry… to emphasize the importance of operators planning for satellite identification in advance so that they are able to troubleshoot potential issues, particularly for multi-satellite deployments."[87] Additionally, it adopted a requirement that operators coordinate with the 18th Space Control Squadron or similar civilian entity for registration and exchange of orbital information. These points were all adopted at an FCC meeting on April 23, 2020.[88]

CubeSats are often bulk launched from containerized deployment devices. The FCC has noted that once the device has deployed all the CubeSats it is carrying, it becomes orbital debris.[89] It would be beneficial to the FCC and the space community if instead, the free-flying deployment devices could act as on-orbit technology testbeds for lower TRL tracking and identification devices and schemes. Efforts to this effect have been announced.[90]

In general, CubeSat-specific (and nanosat-specific) regulation has lagged CubeSat technology development, but as CubeSats become ever more popular and ubiquitous, pertinent regulations are being developed, both domestically and internationally.

So, What's Next?

So where should we go from here? To support the development of sound policy by regulators, it is important that they be informed of the art of the possible. This includes not just analysis but also demonstration of potential solutions. It is entirely possible to carry out a small-scale field demonstration of the various techniques and technologies that have been previously described.[91] The goal would be to demonstrate various means to ID a testbed of various outfitted CubeSats, and to greatly reduce the unidentified fraction among the other CubeSats in the launch. Such a demonstration would align with the stated goals of at least one regulatory body, the FCC.

Conclusion

It is likely that the CubeSat revolution will continue as the cost to construct and launch them to orbit continues to decrease.[92] However, if we cannot find a way to bend the curve and reduce the fraction that arrive in space non-functioning and/or remain unidentified, more satellites will suffer loss-of-mission, to the detriment of all space users. As has been shown, the inability to ID a satellite may cause its early demise, while a non-functioning CubeSat may be difficult to ID. Both issues need to be worked. The path forward will involve interconnected mitigation efforts that are in harmony with the CubeSat culture, and which fit CubeSat design, budgets, and schedule constraints. There are many parties that will need to be engaged in any solution; regulators, SSA/STM providers, CubeSat owner/operators, launchers, and indeed many other actors in the space arena. The set of solutions includes encouraging best practices for design, launch, and operation, frequent and early communications amongst the various entities involved in getting the CubeSat on-orbit, and practical solutions for independently identifying space objects.[93] All the pieces are on the table. We just need to put the puzzle together.

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[2] Independent of the state of health of the space object.

[3] *IADC Space Debris Mitigation Guidelines*, Issued by Steering Group and Working Group 4, IADC-02-01 Revision 1 September 2007, p. 8, https://www.iadc-home.org/documents_public/view/id/82#u, accessed March 3, 2020.

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[7] Braun, B. & S. Herrin (2016). *The more, the messier: ORS-3 lessons for multi-payload mission deployments*. 1-10. 10.1109/AERO.2016.7500582.

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[9] Catalog of space objects, maintained by 18th Space Control Squadron (18 SPCS), Vandenberg AFB, CA, https://www.space-track.org/#/catalog, accessed April 14, 2020.

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[16] https://www.kirtland.af.mil/About-Us/Fact-Sheets/Display/Article/826059/space-test-program/, accessed April 8, 2020.

[17] *CubeSat Design Specification*, rev. 13, https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/56e9b62337013b6c063a655a/1458157095454/cds_rev13_final2.pdf, accessed March 3, 2020.

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[20] Mathewson, S., "India sets record with launch of 104 satellites on a single rocket -Space.com", Space.com, https://www.space.com/35709-india-rocket-launches-record-104-satellites.html, accessed May 2020.

[21] Cognizant that "Space Domain Awareness" (SDA) is a current term of art in certain circles, having subsumed "Space Situational Awareness" (SSA), SSA is used in this work as it incorporates the elements important to the tracking and identification of CubeSats and nanosats.

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[26] n! is n multiplied by every positive integer less than n. It is used to determine how many different combinations are possible.

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