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Evaluating the Risk Posed by Propulsive Small-satellites with Unencrypted Communications Channels to High-Value Orbital Regimes

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ABSTRACT

Propulsion systems for small-satellites are approaching the market. At the same time, some operators do not encrypt their communications links, creating the near-term potential for an unauthorized actor to send spurious commands to a satellite. At worst, an unauthorized activation of the propulsion system could precipitate a conjunction. Aside from the potential loss of system hardware, the reputational costs to the industry of such an incident could be significant and far-reaching. To establish a physical basis for the feasibility of this risk, we simulate the potential altitude increase from a 300 km circular orbit generated for a 10 kg nano-satellite coupled with each of the propulsion system types under advanced development. We find that chemical reaction systems enable the satellite to access all altitudes within LEO over short time domains and that electrostatic propulsion is capable of reaching GEO, though over long time domains. Manufacturers, launch service providers and brokers, regulators, and the CubeSat community all have potential roles to play in managing this risk.

OVERVIEW

Small-satellites, particularly those meeting the CubeSat design specification, historically have not featured propulsion systems. Though some operators have used techniques such as differential drag to manage position, particularly for constellations, propulsion would enable a range of more sophisticated missions. A small-satellite with a propulsion system could perform the following:

- Dispersal maneuver to scatter away from a primary payload
- Constellation deployment and formation flight
- Low-Earth orbit changes and corrections (altitude or inclination)
- Low-Earth orbit life extension by drag compensation
- Maneuvers with delta-V greater than Earth’s escape velocity for interplanetary missions
- End-of-mission deorbiting

A number of efforts to realize small-satellite propulsion are in the advanced R&D or production stages, as further described below. However, alongside the benefits that propulsion would provide to smallsat mission designers and operators, this emergent technology may yield new risks.

In particular, some smallsat operators do not encrypt their telemetry, tracking, and control (TTC) or mission data communication links. Though systematic data does not exist on the encryption status of small-satellite mission communication links, informal conversations within the smallsat community and economic self-interest suggest that university missions are the primary users of unencrypted links.

The combination of a propulsion system and unencrypted TTC links raises the possibility of an unauthorized actor sending spurious commands to a satellite. At worst, an unauthorized activation of the propulsion system could precipitate a conjunction. Aside from the potential loss of system hardware, the reputational costs to the industry of such an incident could be significant and far-reaching.

In this paper, we identify the capabilities of small-sat propulsion systems that may be deployed in the near term, which we define to mean Technology Readiness

Level (TRL) 6 or higher. We couple these propulsion systems to a reference nano-satellite and simulate the orbital altitude change possible to set an outer physical limit on the orbital regimes potentially held at risk by an aberrant small-satellite.

The goal of this analysis is to identify whether the combination of unencrypted TTC communications and propulsion systems under development could—in principle—pose a meaningful threat to high-value spaceborne assets, such as commercial, military, and scientific satellites or human spaceflight. Further, should our analysis show that a meaningful risk does not currently exist, the results will define a checkpoint for further investigation. The eventual development of more powerful smallsat propulsion systems may necessitate a re-evaluation. Lastly, regardless of the likelihood of a conjunction, there remains the threat to the operator of losing the value of their asset if an unauthorized command leads to the activation of the propulsion system. This could result in the satellite relocating to an orbit that limits its operation usefulness, the system's lifetime, or the rapid deorbit of the satellite.

The authors fully acknowledge the limits of our analysis; the scenario under consideration includes numerous simplifying assumptions. However, this worst-case, zero-order analysis is an appropriate first step because it represents an absolute limit on possibility. If a propulsive satellite does not have sufficient energy to cross the orbit of another high-value asset, no further discussion about the feasibility or likelihood of the threat is worthwhile. We welcome further discussion with all stakeholders about our analysis and its implications for particular missions.

RISK BASIS

Use of Small-Satellites

Smallsats are considered the next generation of spacecraft, as the incentive for designing, building, and launching more compact payloads has grown exponentially in the past two decades. They can be classified by volume or mass, with the latter being the most practical to determine launch and propulsion requirements. Although no official nomenclature apart from the "CubeSat" standard introduced in 1999 exists, the following classification is commonly adopted by the scientific and engineering community, and will be used in this paper:

- A *small-satellite* has a mass below 500 kg
- A *micro-satellite* has a mass between 10 and 100 kg
- A *nano-satellite* has a mass between 1 and 10 kg
- A *pico-satellite* has a mass between 0.1 and 1 kg
- A *femto-satellite* has a mass below 0.1 kg

The CubeSat standard was defined by California Polytechnic State University and Stanford University, and has been adopted by educational institutions, government agencies, and private industries all around the world. Each unit, also referred to as a "U", has a tight volumetric constraint (a cube with 10 cm-long edges), and a maximum mass of 1.33 kg (although exceptions exist). Combinations of these units can be made to form *n*-U satellites, with *n* typically between 1.5 and 6.

Reference 4 offers an extensive survey of worldwide pico- and nano-satellite missions before 2009. Figure 1 and Figure 2 illustrate the past and projected number of launches per year. A small number of satellites under 10 kg were launched before 1962, since the payload requirements were limited by the launch capabilities in the early years of space-flight. As the space-race led to a rapid increase of payload mass limits, larger satellites were favored to house more advanced instrumentation and communication devices. However, technological progress in the miniaturization of electronic components made it possible to conceive smaller systems, still capable of providing significant contributions.

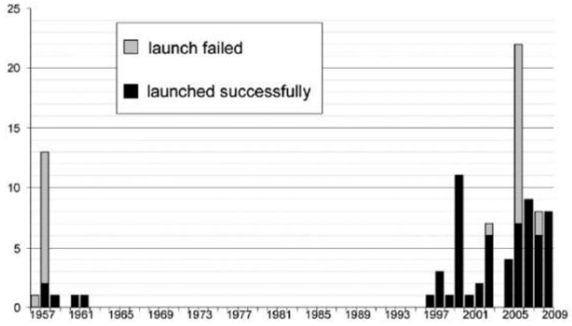

Figure 1: Pico- and Nano-satellites Launched between 1957 and 2009[4]

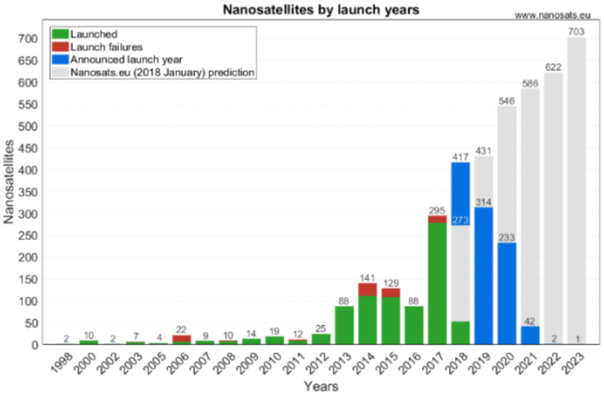

Figure 2: Nano-satellites Launched between 1998 and 2023 (projected)[5]

First designed for educational purposes, small-satellites became low-cost, low-risk, and rapid solutions for space-exploration, technology demonstration, and commerce at the end of the 20th century. Large constellations for communications such as Orbcomm and GlobalStar (1998) were deployed, and CubeSats were popular for training purposes. Between 2012 and 2013, the number of attempted launches of nano-satellites increased by 330%, and one industry analysis projects there will be between 2,000 and 2,750 launches of satellites under 50 kg between 2014 and 2020[6]. With the personal electronics industry driving down the cost, mass, and size of microelectronics while simultaneously improving their performance, small-satellites are now an affordable pursuit for start-up companies around the world, funded with more venture capital every year. Advances in additive manufacturing technology have also significantly changed the design capabilities and development costs of pico- and nano-satellites (typically ranging between $100,000 and $2 million), mitigating the financial consequences of potential launch failures.

There is a significant interest in small-satellite missions because of the capabilities these low-mass systems can now offer. The lower cost of development and access to space is expected to lead commercial funding to exceed government- or university-sponsored missions after 2018. Most of these satellites will be used for Earth observation and remote-sensing, including applications for natural disaster prevention and monitoring, environmental pollution, resource monitoring, and agricultural optimization. Another application is technology demonstration in areas like thermal protection, avionics or instrumentation. Finally, operational use of small-satellites, for communications, scientific measurements, and space exploration cover most of the remaining mission concepts. However, these satellites are typically confined to their dispersal orbits, and although an increasing number of launch opportunities exist, most are dependent on the primary payload's delivery orbit, which adds significant constraints to the mission planning. Government agencies such as NASA, ESA, and JAXA offer rides as secondary payloads to LEO, known as "ride-sharing" or "piggy-backing", but private companies such as Rocket Lab and Vector Space Systems are now designing dedicated launchers to meet the specific needs of payloads under 500 kg[7]. The European Union is also identifying competitive solutions to answer the demand within the Horizon 2020 program[8]. Figure 3 shows the cumulative number of nano-satellites designed by type, illustrating the popularity of 3 and 6U CubeSats.

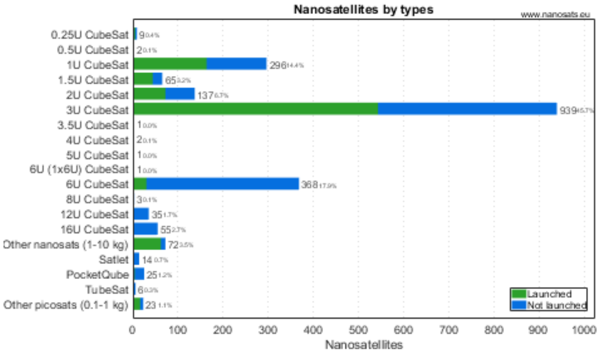

Figure 3: Cumulative Nano-satellite Designs by Type[5]

According to the Union of Concerned Scientists' database[9] (updated 8/31/2017), 1,738 satellites are active in Earth orbit, with 6.6% having an unreported launch mass, 42% a mass under 500 kg, and 20% classified as nano-satellites or smaller. However, the nano-satellite database by Erik[5] estimates that there are almost 600 nano-satellites in orbit. Among the reported active satellites under 10 kg, almost all are in low-Earth, near-circular orbits, with altitudes roughly ranging between 300 and 900 km, and inclinations between 0 and 120°. It is interesting to note that 70% of these satellites are in a sun-synchronous orbit, largely due to the heavy presence of Planet's Earth-imaging CubeSats. With almost 200 Earth-imaging satellites in operation, the company currently controls the largest fleet.

Satellite Encryption

One area of increasing interest has been the use of encryption on small-satellites. We focus our analysis on satellites potentially subject to U.S. regulations, though the analysis could be extended to other jurisdictions, drawing frequently from a recent analysis by the Aerospace Corporation regarding small-satellite policy compliance.

Satellites "owned or controlled" by the U.S. Department of Defense must have encrypted up- and down-links, as mandated by DoD Instruction 8581.01.[13] For U.S. federal spacecraft outside of DoD, a NIST framework determines whether encryption is required based on the "criticality and sensitivity of information transmitted."[13]

The revised Cybersecurity Policy for Space Systems Used to Support National Security Missions (CNSSP-12, Feb. 2018) includes flow-down requirements to most commercial operators of systems leased by or otherwise supporting DoD regarding the encryption of communication links.[10]

Finally, DoD or other federal agency sponsorship of an academic satellite may create flow-down requirements for encrypted links. Further, for those satellites subject to NOAA's Commercial Remote Sensing Policy, the regulator must approve a licensee's Data Protection Plan, which must include information on link protection.[14]

This policy patchwork results in a class of academic and commercial operators not subject to a government-imposed encryption requirement, with the Aerospace Corporation noting that there is "no current requirement to encrypt up-links, regardless of satellite capability for propulsion, proximity ops, etc."[13] That said, to the extent commercial operators are not bound by governmental regulators, there remains a commercial interest in encryption. The data sensed by for-profit operators is an essential ingredient in its product offering(s). Preventing its misappropriation by customers or competitors is a rational defensive move. Indeed, at least one NewSpace commercial imaging operator publicly acknowledges encrypting its data down-links.[11]

Furthermore, commercial operators' frequent use of constellations amortizes the fixed costs of encryption implementation among many units. Commercially-available cryptographic chips under development for small-satellite use are on the scale of tens of thousands of dollars. Price breaks for bulk encryption chip purchases and being able to apply the system design to multiple satellites eases the pain of encryption for commercial operators and is not analogous to the low-budget, one-off satellite context of a university team.

For university teams not bound by U.S. government or other governments' encryption requirements, there is no similar private interest in protecting mission data. Instead, as a cultural value within the scientific community, data is meant to be shared. Though there is certainly a self-interest in securing TTC links against the possibility of someone interrupting the mission, such a consideration, particularly once costs are considered, does not appear to hold the same salience as for commercial operators.

Small-satellite Propulsion Development

In this paper, only propulsion systems using high-velocity propellant ejection are considered[15,16,17,18,19]. The energy to produce thrust is therefore delivered by stored enthalpy, chemical combustion or electric sources, and used to accelerate matter. Different parameters are used to categorize these propulsion systems and determine mission requirements:

The *total impulse* [N.s] is the thrust force integrated over the run time. This parameter can only be used to compare propulsion systems if it is assumed that they carry the same mass of propellant. Attitude control systems requiring fine pointing also use the term minimum impulse bit (MIB), which is the smallest repeatable impulse delivered by a thruster.

The *specific impulse* (Isp [s]) is the total impulse per unit weight of propellant, or for constant values, thrust per unit mass. In general, the higher the specific impulse, the less propellant required, which can translate as a measure of performance. However, caution is to be used since Isp alone does not give an indication of the thrust level. Low mass flow systems can exhibit very high specific impulse, but also very low delivered thrust. Care should also be taken when specifying Isp at sea level or in vacuum. In this paper, only vacuum Isp values are considered since the evaluated systems are designed for in-space use.

The ideal theoretical velocity change *"Delta-v"* (Δv [m/s]) derived from the Tsiolkovsky rocket equation, is a function of the mass loss during powered flight. It is used to describe the propulsive requirements of a maneuver, ranging from m/s for low-Earth orbit drag compensation, to km/s to move within the Earth-Moon system. Δv capability of a propulsion system is specified for a given spacecraft total mass.

The *propulsion dry mass fraction* is a measure of the ratio between the propellant mass expended to deliver the thrust, and the remaining structural mass. It is obtained by dividing the "dry" mass by the total mass of the propulsion unit (including the propellant or "wet" mass). Unfortunately, this value is rarely specified by manufacturers, and does not scale linearly with propellant loading. This value typically decreases as propulsion systems scale upward.

Chemical propulsion

Chemical propulsion utilizes the enthalpy stored in the propellant itself: the system's internal energy plus the product of pressure and volume. When the energy from a chemical combustion reaction is released, the products are heated to high temperatures, and kinetic energy is harnessed through supersonic expansion in the nozzle. Chemical systems can achieve high thrust, making them the most suitable candidates for launch vehicles. But downsizing chemical propulsion systems for in-space, small-satellite applications can be difficult due to the complexity of miniaturized active propellant handling components (valves, pumps, pressure vessels, etc.) rated to high pressures. The associated dry mass and volume can become significant, producing either insufficient Δv or in certain cases exceeding the system's design constraints. Despite these engineering challenges, advanced-development chemical propulsion systems are:

Cold gas: uses a compressed gas - such as helium, nitrogen, or liquid isobutane (self-pressurized) - delivering relatively low specific impulses (40 to 120s). Their inherent simplicity makes them well-suited for reaction control systems (RCS), with MIBs around 1mN.s, and low-thrust small-satellite maneuvers.

Warm gas: the internal energy of the stored gas is increased through heating with an external electrical source, which improves the delivered specific impulse.

Water electrolysis: Electrolyzers in a water tank decompose the propellant into a mixture of oxygen and hydrogen gas, which is then injected and ignited in a combustion chamber. Isp values are around 300 s, and the inherent safety of a water-based propulsion system is attractive for CubeSat developers.

Monopropellant: utilizes thermal or catalytic decomposition, producing a highly exothermic reaction. Hydrazine and monomethylhydrazine (MMH) are the most commonly used monopropellants, despite their toxicity and strict handling requirements. This increases the associated cost and prohibits development in academic settings. Research efforts now focus on "green" monopropellant solutions, such as AF-M315E developed by Air Force Research Laboratory (AFRL). Controllability, restart, and a specific impulse range between 150 and 250 s makes them ideal for a variety of small-satellite operations.

Liquid bi-propellant: depends on the chemical reaction of an oxidizer and a fuel stored separately. These systems deliver the highest specific impulses (can be up to 450 s, but typically below 300 s), but at a cost of greater complexity associated with independent fluid handling systems. The total mass and volume of a full bi-propellant unit often exceed nano-satellite constraints.

Solid: these systems offer the highest thrust-to-weight ratio by storing both the oxidizer and fuel in the densest, pre-mixed state. Their lack of throttle-ability or restart capability makes them better suited for single de-orbiting maneuvers, with Isp values between 200 and 300 s.

Hybrid: although not space-flight qualified, hybrid systems offer a promising alternative to bi-liquid or solid thrusters. They exhibit higher specific impulse than monopropellants, reduce system complexity compared to bi-liquid systems, and increase controllability compared to solid motors. They have been identified as possible candidates for small-satellite interplanetary missions requiring significant Δv.[25]

Electric propulsion

Electric propulsion (EP) has been used extensively on spacecrafts since the 1960s, but recent interest in small-satellites has boosted research and development in electric micropropulsion. Although EP units can be simpler and more compact than their chemical counterparts, research efforts have been focused on decreasing their considerable power requirements. EP systems use electrical power to heat or directly accelerate a propellant. The external energy source can be provided by chemical, nuclear, or solar sources, and deployable solar panel area typically limits the power budget of nano- and pico-satellites below 30 W. Mars Cube One (MarCO), the 13.5 kg, 6U interplanetary CubeSats launched in May 2018, can generate up to 35 W near Earth and 17 W near Mars with two square-foot solar arrays[26]. There are three main categories of EP systems:

Electrothermal: electric energy is used to heat the propellant and increase its enthalpy before expanding it through a nozzle. This is in effect similar to warm-gas propulsion, but technically differs because only the flow of propellant is heated to high temperatures before the nozzle throat, compared to the bulk gas in a storage tank or a separate reservoir. These two types can be merged for simplicity. Resistojets generate heat with high electrical resistance that is transferred to the working fluid primarily through convection.

Electrostatic: uses electric fields to accelerate charged particles. Ion thrusters (including radio-frequency), Hall thrusters, Colloid-electrospray thrusters, and field emission electrostatic propulsion (FEEP) are all types of electrostatic systems. The low mass of the non-neutral particles (mostly ions) leads to low thrust levels but high specific impulse. The power requirements of Hall thrusters still exceed small-satellite capabilities (over 100 W) and are not considered here.

Electromagnetic: uses electromagnetic fields to accelerate gas heated to a plasma state. The most common types of thrusters are magneto-plasma-dynamic (MPD), pulsed-plasma (PPT), and vacuum arc thrusters (VAT). Minimum impulse bit values are specified for systems designed to operate in pulsed mode, and MPD systems still require power levels beyond those achievable on small-satellites.

As a result of this analysis, propulsion systems for satellites weighing less than 10 kg, and at a TRL of 6 or higher will be divided in the categories presented in Table 1. Thrust ranges are approximate for nano- and pico-satellites, since they depend on the scale of the propulsion system and the throttling capabilities. The dry mass ratio range has also been roughly approximated given the scarcity of data for fully integrated propulsion units for satellites of this scale. Most developed concepts (monopropellant, electrostatic) specify the thruster mass, but the propellant storage system can be customized to specific mission requirements.

Table 1: Performance Metrics of Small-satellite Propulsion Options

Propulsion type	Thrust [mN]	Isp [s]	Dry mass ratio	TRL
Cold gas	$0.1 – 10^2$	40 – 80	0.5 – 0.95	9
Chemical reaction	$1 – 10^4$	150 – 300	0.4 – 0.8	6 – 8
Warm gas/ electrothermal	1 – 50	70 – 300	0.4 – 0.85	6 – 9
Electrostatic	0.01 – 10	800 – 5000	0.5 – 0.9	6 – 9
Electromagnetic	$10^{-5} – 1$	500 – 2000	0.8 – 0.99	6 – 9

SCENARIO DESIGN[a]

Distinctions from Anti-satellite Attacks

An Anti-Satellite (ASAT) attack is any course of external action that may cause temporary and reversible interference or permanent damage on a spacecraft, a ground station, or the links between them[1]. Space-based kinetic energy weapons, also known as Kinetic Kill Vehicles (KKVs) or co-orbital kinetic kill ASATs, are kamikaze spacecraft designed to destroy orbiting targets on contact using the large amount of kinetic energy that orbiting spacecraft have. No warheads or explosives are needed. Satellites in orbit move along predictable trajectories at high speeds. Furthermore, being nearly impossible to hide, satellites are highly valuable assets that are difficult to protect. At such large speeds, collisions with even very small objects can be disastrous[1].

The risk posed by the unauthorized access of a propulsive small-sat shares features with that posed by kinetic ASATs. At worst, a propulsive small-sat as becomes a kinetic kill vehicle. As Galton[2] states, "A large percentage of space assets can be considered dual use in that they have distinct value to the military, civilian, and scientific sectors of society but simultaneously pose a threat to the space security environment."

However, we recognize that purpose-built weapons incorporate essential design features almost certainly not present in foreseeable nano-satellites. From an orbital mechanics perspective, intercepting a spacecraft using a KKV at LEO is one of the hardest maneuvers ever performed, "the equivalent of hitting a bullet with a bullet."[3] Even though a satellite orbit is predictable and may be known well ahead the interception, the exact position of the target has a large uncertainty. In fact, a KKV needs to steer itself to hit the target at high speed and high acceleration.[3] Thus, military KKVs have some kind of seeker, guidance, and closed-loop control to track, follow, and finally destroy the target. Without any such a tracking system, purposefully hitting a target at LEO is improbable, but still possible. In other words, a misappropriated satellite without any kind of tracking system can only perform open-loop mid-course correction maneuvers.

Simulated Scenario

Our reference nano-satellite begins parked in an equatorial circular orbit at an altitude of 300 km. The propulsion system is turned on until the propellant mass is completely depleted. The thrusting direction is assumed to be along track. Although this is not exactly the direction that maximizes the final altitude, it can be shown that the optimal thrusting vector oscillates around this direction[29,30]. We assume the satellite meets the 25-year guideline for debris mitigation, meaning it orbits below 700 km to self-clean or has a propulsion system for deorbit, implying that a retrograde burn would simply hasten existing deorbit plans.[27]

Since the major secular changes in semimajor axis and eccentricity in LEO are due to drag, the perturbation caused is added to the simulation with a very simple exponential model with atmosphere density varying with altitude (See Table 8-4 in Ref. 27). The spacecraft's side facing the drag force is assumed to be 200 cm^2 (two CubeSat units) and the drag coefficient is taken as 2.1. Even though thrusting for long periods is not possible for several propulsion systems due to thermal or power considerations, the analysis establishes a physical outer bound and gives the minimum time of flight that a spacecraft with a particular propulsion system may take to reach an orbit of a certain altitude.

We note that changing inclination or RAAN (Right Ascension of Ascending Node) is not necessary here. Major RAAN and inclination changes are expensive, especially in LEO. In fact, even in the same orbital plane, an attacker can wait for natural phenomena to perform the needed RAAN change. For example, the J2 component of the Earth gravity field differentially rotates the orbital planes by a RAAN secular change for

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[a] The Python code described here and reported below may be requested by contacting the authors at their corresponding email addresses.

different altitudes and inclinations[27]. Once a RAAN change is obtained, inclination changes are unnecessary with a conjunction still possible. In fact, relative linear momentum would be an essential element of an attack profile.

Therefore, in order to get a first order estimate of the sphere of influence an attacker could reach for our reference designs, it is only necessary to consider in-plane maneuvers. In other words, an attacker could get to higher orbits by performing in-plane instead of out-of-plane changes.

In the simulation performed, the misappropriated smallsat is assumed to weigh 10 kg (largest of the nano-satellite class) with 50% of the total mass allocated to the propulsion system, the remainder being the functional payload. Five propulsion systems in development are selected from the categories in Table 2, and the performance metrics are assumed to remain constant as the units are scaled up to a total mass of 5 kg. The respective average thrusts, Isps, and dry mass ratios are used to estimate the total mass of propellant, average mass flow rate, and consequently satellite mass and acceleration varying with burn time.

Table 2: Existing Propulsion Systems Selected for Orbit-Raising Simulation

Manufacturer	Name	Thrust [mN]	Isp [s]	Dry mass ratio
Microspace[20]	POPSAT/HIP1	0.2	31.8	0.78
ECAPS[21]	1N-HPGP	1000	235	0.43
Busek[22]	Micro Resistojet	10	150	0.87
Busek[23]	BIT-3	1.24	2300	0.48
NASA/Primex Aerospace[24]	EO-1	0.86	1400	0.86

SIMULATION RESULTS

The following figures show the altitude the reference propulsive nanosat systems can reach versus time of flight for the maneuver. The quantitative results are summarized in Table 3. Most systems can soar to higher altitudes remaining in LEO. Only orbits up to GEO were considered in the model, but with electrostatic propulsion, a smallsat could reach MEO, GEO, and potentially even higher orbits. High thrust, low Isp systems (chemical reaction) can quickly reach targets in LEO (< 2 h), but low thrust, high Isp capabilities enable smallsats to reach much higher altitudes but require very long flight times (over 390 days to GEO for the electrostatic propulsion system considered in the analysis).

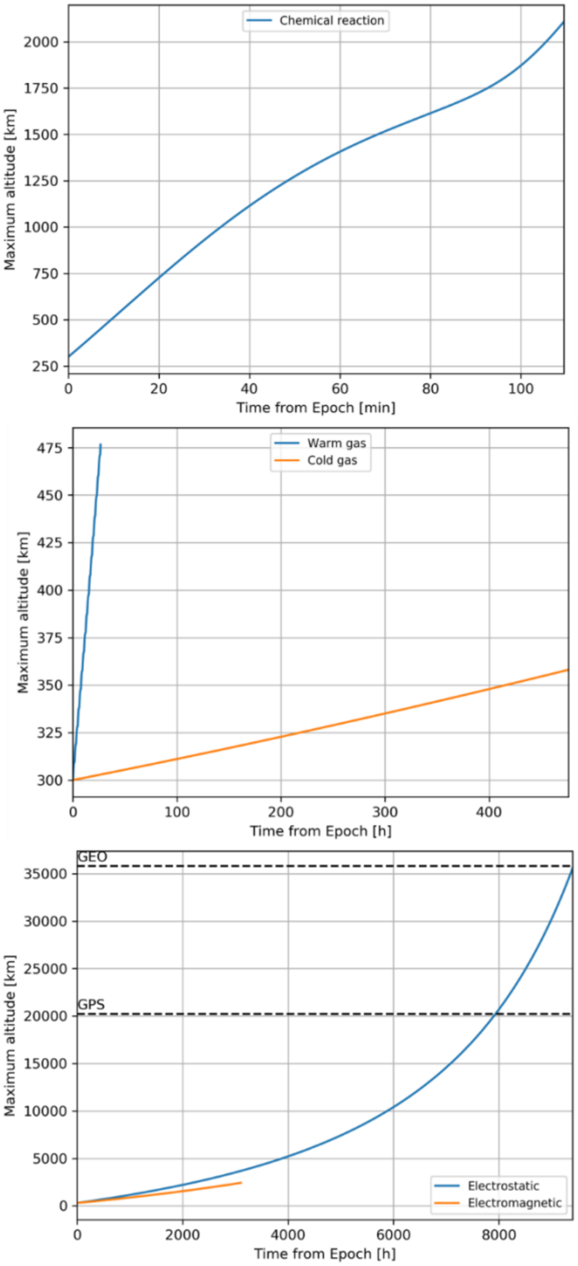

Figure 4: Altitude vs. Time from Epoch for a 10 kg Nano-satellite with Propulsive Capabilities

Table 3: Orbit-raising Simulation Results with Selected Propulsion Systems

Propulsion Type	Maximum altitude [km]	Time of flight [h (days)]
Cold gas	360	480 (20)
Chemical reaction	2110	1.8
Warm gas/ electrothermal	480	27
Electrostatic	35600 (max limit at GEO)	9400 (392)
Electromagnetic	2420	3100 (129)

DISCUSSION

Chemical reaction propulsion systems may pose a credible risk to other objects in LEO, which, as shown in Table 4, is the most populous region of space.

Table 4: Number of Satellites in Circular Orbits, Per Orbital Regime[b]

Orbital Regime	Number of Satellites (all masses)
LEO (<2,000 km)	1,072
MEO (2,000-~35,000 km)	94
GEO (~35,000 km)	529

Stakeholders should consider whether it would be feasible to react to an unwarned maneuver prior to a conjunction.

Though other propulsion systems, particularly electrostatics, indicate an ability to potentially hold additional high-value orbital regimes at risk, the time of flight and coexistent likelihood of detection likely make such an attack unattractive.

As noted above, the goal of this analysis is strictly to establish physical plausibility. Simply because kinematics suggests that a particular propulsive system can reach a certain altitude does not mean a successful attack is probable. In order to launch an attack on an orbiting spacecraft without any closed-loop tracking capabilities, the attacker must accurately know the position and velocity of the target and the interceptor at a certain epoch and propagate both orbits with a very accurate orbit propagator. Orbit prediction is usually hard, especially for a spacecraft in LEO, where drag is the most important perturbation. Drag is a hard-to-predict phenomenon that presents unpredictable hourly variations.

In order to perform mid-course corrections, the attacker may need ongoing communication with the satellite. The intruder would thus need a worldwide, or at least an extensive, network of ground stations available. Additionally, it is probable that the satellite would have to perform an attitude maneuver in order to communicate with a ground station, which means that thrusting and communicating at the same time might not be possible. Finally, the tight power budgets found on many nano-satellites could make a successful intrusion challenging because the attacker may not know that capabilities or sensitivities of the system.

POLICY CONSIDERATIONS

Any satellite, including a small-satellite, with a significant propulsive capability should secure its TTC links against unauthorized access.

Though the likelihood of success by an attacker and the probability of collision may be low, the reputational risk to the small-satellite community even without a resulting conjunction may be significant. Given the increasing prominence of this sector within the space industry and governments' increasing emphasis on space investment, an aberrant event may lead to calls for restrictive regulations that would slow the maturation and acceptance of small-satellite technology.

Space Policy Directive-3 defines a framework for future U.S. policymaking on space traffic management. The document envisions a future pre-launch certification process that includes "consideration" of a minimum set of factors, of specific relevance "encryption of satellite command and control links."[35] However, at best such requirements—likely years from implementation—would apply only to those missions with a U.S. nexus (operator, launch provider, etc.).[10] Since space represents a global commons, shared norms are necessary.

To generate global coverage, as well as to take advantage of an opportunity to cooperatively design a U.S. policy that will eventually become federal regulation, we offer several approaches that smallsat community stakeholders could consider in formulating a response to the risk demonstrated above.

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[b] We classify here objects in circular orbits as those with eccentricities less than 0.1. Data via Union of Concerned Scientists, ref. 9.

Propulsion Module Manufacturers

As product originators, propulsion module manufacturers know the customer base best. Further, their incentive to protect their products' viability by ensuring appropriate regulations is strong, creating a clear logic for manufacturers to make encryption a standard sales term. Elegantly, unlike national regulation, a step taken by the module manufacturer would apply to satellite customers regardless of nationality.

Similar to export compliance, module manufacturers may need to take steps to "know your customer" and ensure that the recipient of the module is truly capable of integrating protected communications channels. Though there are certainly costs involved in this effort, they may be low relative to the risks of not requiring protection.

To avoid customers shopping for the least restrictive terms, module manufacturers worldwide could consider creating a cooperative mechanism to facilitate a standard policy. Self-regulation of this sort is common across industries and is often effective when companies are better placed than governments to address a market externality. Cooperative mechanisms need not be elaborate, and clear terms of reference defining how such an agreement would operate could allay anticompetitive concerns.

Launch Service Providers and Brokers

Launch service providers and brokers represent a second potential chokepoint for protection: nothing gets to orbit without them. As a matter or corporate citizenship and sustainability, these entities could consider backstopping a propulsion module manufacturer self-regulatory mechanism or developing their own policy of encryption as a precondition of accepting a propulsive payload. As with the module manufacturers, engaging launch service providers sidesteps intergovernmental negotiations and captures any nation's operators seeking to launch with that platform.

Since university missions appear to be the least likely to secure their communications links, the brokers that often play a pivotal matching role between customers and launch service providers could also establish corporate policies of requiring encryption as a condition of the transaction. Brokers are well-positioned to advise their clients on the latest norms and trends.

Regulators

If industry fails to act, governments worldwide could consider coordinated efforts through multilateral export control mechanisms such as the Wassenaar Arrangement and the Missile Technology Control Regime. Regulators could seek to establish a norm of encrypted TTC links as a license condition when exporting propulsion systems and develop this as a regime-wide best practice.

CubeSat Community

To the extent that propulsion systems will be compatible with the CubeSat specification, community stakeholders could consider revising the specification to encourage or require protected links with propulsion systems, potentially to include expanding General Requirement 3.1.5.

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