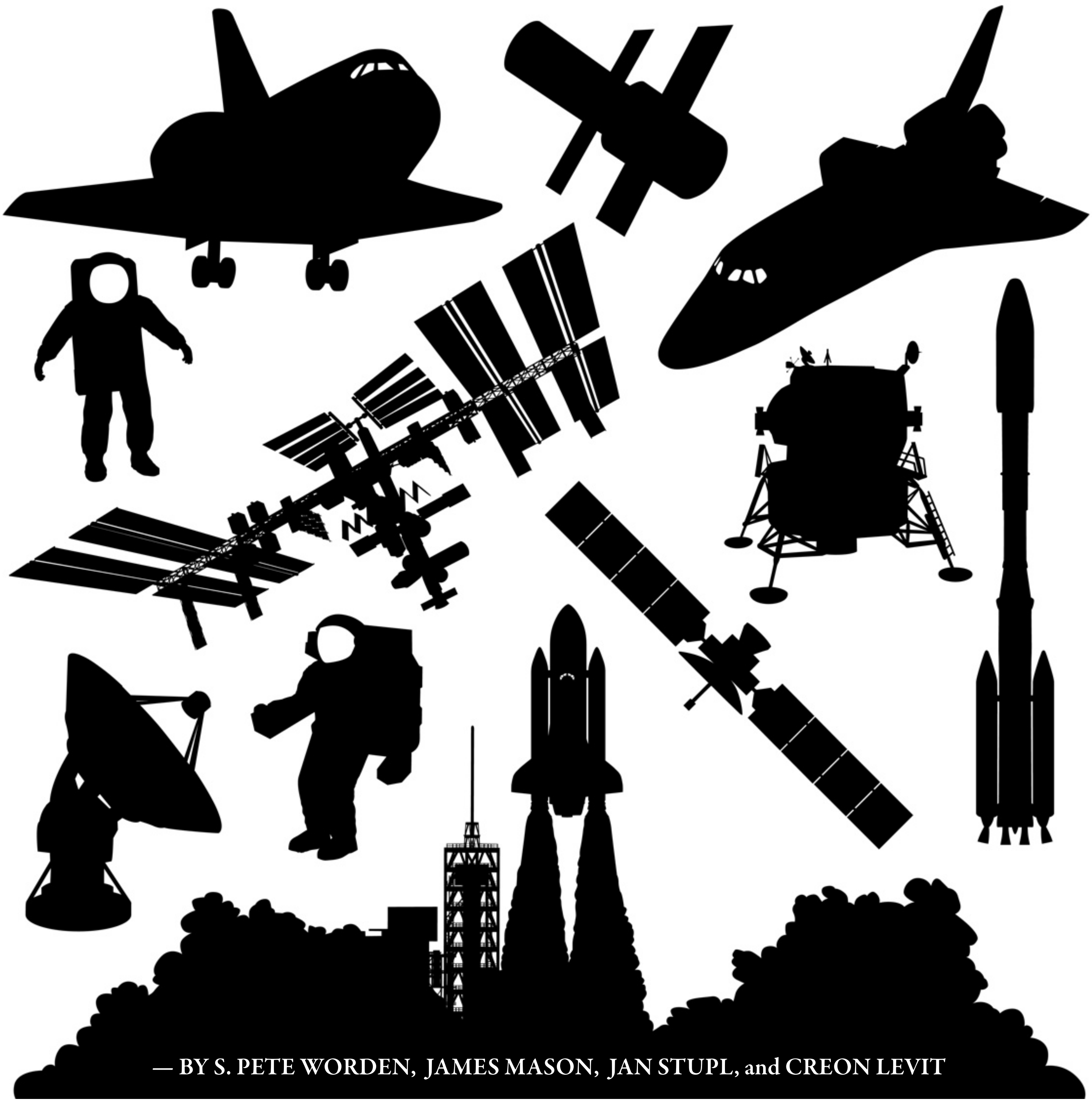
How to Work in the New Space Security Environment



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INTRODUCTION

During the Cold War, space was dominated by the United States and the Soviet Union. Today, more than 40 countries [source: UCS satellite database] operate satellites in orbit. If one includes the members of the European Space Agency (ESA), nearly 30 countries have access to space launch vehicles. Excluding ESA, seven countries have repeatedly demonstrated launches, and there are new players on the verge of joining that exclusive club. These include some truly commercial entities, but also Iran and North Korea. The increasing number of players presents a new and challenging space security environment that demands new approaches.

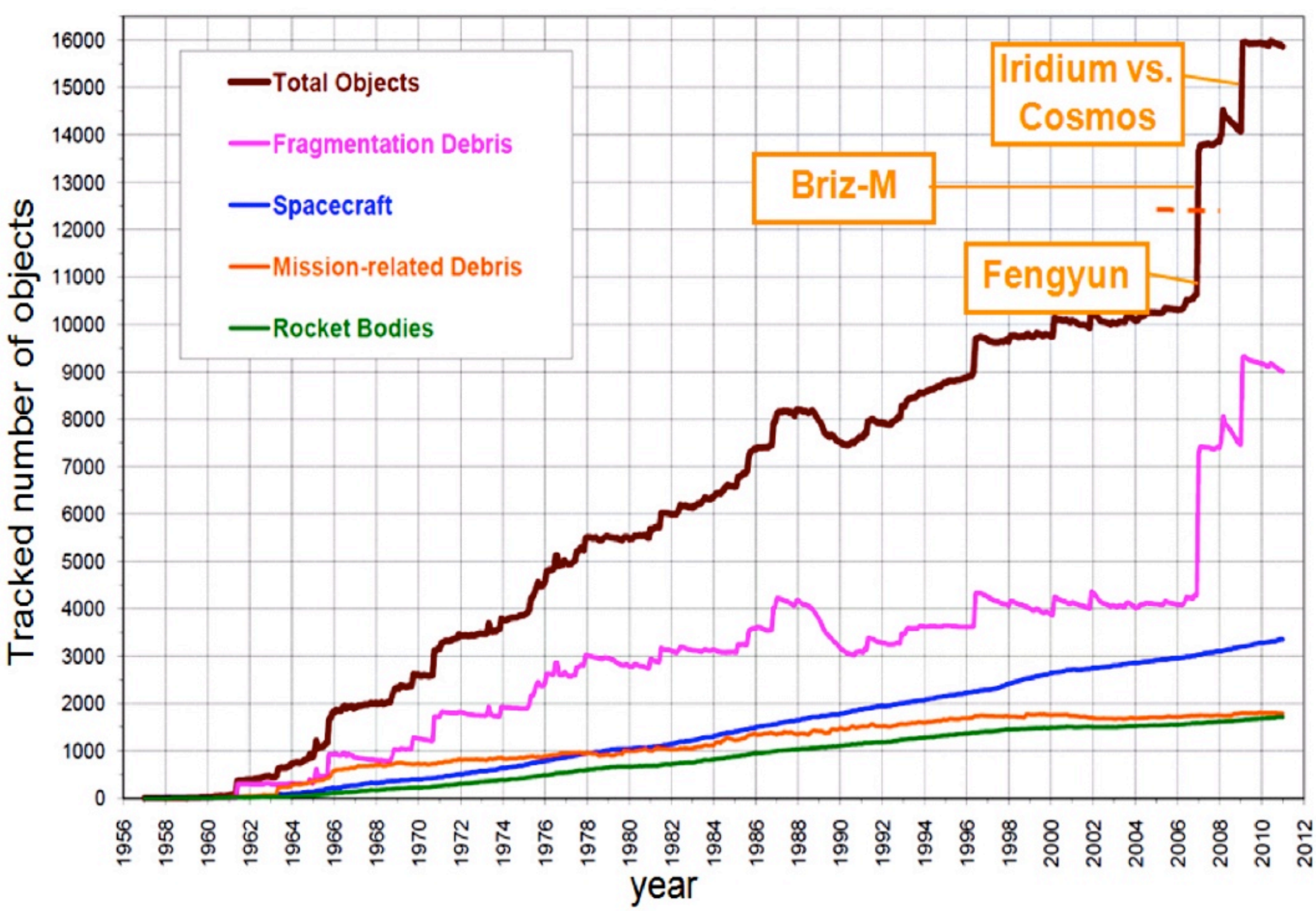
Along with achieving a basic strategic missile capability, most space faring nations have demonstrated a fundamental prerequisite for an impact anti-satellite (ASAT) capability. Only a few have actually performed high precision rendezvous or targeted strikes, but having a space launcher brings one closer towards the possession of an impact ASAT weapon.

Simply testing impact ASAT weapons, besides having obvious political consequences, presents problems for any operators in the space environment: in orbits above about 800 km any generated debris can remain in orbit for decades or even much longer. Every fragmentation event starts a cosmic game of billiards, spreading debris and endangering assets in other, similar orbits.

In the past, there have been few deliberate fragmentation events, but also a fair number of accidental fragmentations resulting from explosions and collisions. Altogether these lead to an impressive increase in the number of space debris objects (see Figure 1).

In some popular orbits, simulations indicate that the number of fragments has reached a density where the new debris produced by collisions is exceeding the natural re-entry rate due to atmospheric drag, leading to a runaway effect known as the Kessler Syndrome. [1] Keep in mind that these orbits became popular because they are useful for human endeavors. The increased collision risk for satellites in these orbits is already noticeable, reducing expected satellite lifetime by a few percent. [2] For satellites worth billions of dollars this translates into real money.

Figure1: Objects in Earth orbit by object type as cataloged by the U.S. Space Surveillance Network: “Fragmentation debris” include satellite breakup debris and anomalous event debris, “mission-related debris” include all objects dispensed, separated, or released as part of the planned mission. Source: NASA Orbital Debris Program Office, *Orbital Debris Quarterly News*, Vol. 14, Iss.1 (2010). Major debris events annotated.



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In short, space has become more congested and more dangerous. Combine that with times of challenging budgets and it is clear that the old way of flying a few highly capable, and very expensive satellites is no longer feasible. The risk that one of these critical assets is disabled in a time of need, through hostile or accidental means, is just too high. The excessive cost and complexity of these systems also means that systems-level redundancy is traded for extreme risk aversion in the engineering cycle, leading to increased cost. Spares are simply infeasible in this self-perpetuating cycle. Large launch vehicles take months to prepare, and keeping them on standby for emergencies is just too costly.

Nation's and multi-nation coalition's security has become more dependent on space infrastructure; the United States most of all, as it leads the revolution towards net-centric warfare. We are facing the dilemma of depending on an infrastructure that is increasingly difficult to protect.

We can mitigate this dilemma if we can manage to do three things: 1) leverage recent advances in consumer electronics to produce large numbers of small cheap satellites which can provide distributed capabilities, 2) provide low-cost, on demand, micro-launchers to launch these satellites, and 3) implement effective space traffic management (space collision avoidance) systems.

A Paradigm Shift Towards Small Satellites and Distributed Capabilities

The Cold War's reconnaissance satellites represent astonishing technical achievements. Spacecraft like the KH9 Hexagon were close to the weight and size of a typical school bus and provided amazing imaging capabilities. Modern systems are even more impressive. However, building up redundant and easily replaceable capabilities based on these assets is just not feasible anymore. As more actors enter space, the heroes of the Cold War have lost their main strength: their invulnerability. ASATs vs. multi-billion dollar orbital assets is operationally, economically, and unsustainably asymmetric.

The key is to shift to distributed systems. Instead of building one satellite with multiple sensors and communication devices, these sensors and devices can be spread over multiple satellites. Where once there was a bus-sized satellite, there will soon be swarms of smaller, modular, and more agile satellites. If one camera fails, replace the camera satellite. If more communication bandwidth is needed, send up another communication module. This approach has been recognized and is boosted by initiatives like the international QB50 project [3] and DARPA's F-6 project.[4]

The resolution of an optical camera is proportional to its diameter - to get high resolution reconnaissance imagery requires large optics. While this does represent a case where distributed sensors cannot (yet) replace the existing capability, it is also true that the improved cadence offered by a swarm of imaging satellites offers value that occasional high resolution does not. To improve resolution, lowering the satellite's orbit will help and if satellites are cheap then the reduced lifetime and increased vulnerability is not a problem. In the future, new interferometric imaging technology may allow swarms of small satellites to mimic the performance of large single systems - synthetic apertures combining multiple small-satellites, and/or single lightweight "photon sieves" might offer a solution.[5]

Shrinking the satellite's size and weight is not sufficient alone, and shrinking cost can be even more difficult. Currently, satellite components are extremely specialized and risk aversion has bred a cult of only flying heritage systems. Components are rarely flown on real missions unless they have been tested and qualified to the n-th degree. The use of commercial off-the-shelf electronic components is nearly unheard of. This approach is understandable if you build a multi-billion dollar satellite and demand the highest quality controls. However, if the goal is to quickly build large numbers of something that can survive in orbit for relatively short time and can easily be replaced, then the consumer electronics industry can show us how to do it.

Reducing these barriers of entry (i.e. cost) will draw commercial and public interest from outside the aerospace and defense industries. Similar to the development of the Internet and the advances in mobile communications, increasing the number of players often leads to new applications that nobody has heard of before. Today, the only people able to contemplate new space capabilities are the incredibly rich. You and I have very little opportunity to come up with something cool in space and have the resources to realize it. Yet in a few days any of us could develop a new "app" for the iPhone and potentially make a fortune. Similarly, an app-based space economy might soon become reality.

At the NASA Ames Research Center we are building a family of cubists[6] based almost entirely on components that can be ordered online.[7] The PhoneSat project is showing the space community that if we emulate what our neighbors in Silicon Valley do, we can build highly capable satellites quickly and at a small fraction of the cost. PhoneSat is using 3D printing to rapidly prototype components, a smartphone as a (comparatively very fast) flight computer, simple brushless motors for 3-axis momentum wheels, steel tape measure as an antenna, magnetorquer coils printed directly onto a PCB, and pick-and-place procedures to rapidly manufacture low cost solar panels. The project is developing the type of spacecraft bus that will enable ultra-low cost distributed sensor networks. This approach fulfills the hardware requirements for a distributed, redundant, and easily replaceable infrastructure in space. However, getting this hardware up there also requires a new approach for launch vehicles and creates a demand for a micro-launch industry.

Making Low Earth Orbit Accessible Cheaply and on Demand

Imagine designing a rocket to lift a heavy payload, such as a several ton satellite. Chemical propulsion has great heritage, but our big satellite requires a lot of fuel to lift it above the atmosphere and propel it to orbital speeds of over 7 km/s. Lifting this much fuel, along with the payload and rocket structure is difficult, and drives the design to multiple, expendable, stages. Our design quickly grows in complexity, size and ultimately cost. In the new world of shrinking national budgets, this is no longer the best model.

Almost all space launch vehicles are expendable chemical rockets, descendants from Germany's WWII missile program. Today's launch sector, with its severe risk aversion, uses the same propellants, much of the same technology and follows many of the same procedures as it has for the past four decades. So, while computers have gotten a million times cheaper and a million times better since the 1960s, the cost to launch a pound to orbit has not changed at all.

NASA is in the business of space exploration and Earth science. Traditionally, we build big rockets or big satellites that need big rockets. When a big satellite is launched, much of the rocket's lifting capacity is often left unused. In the near-term this provides an opportunity for very small satellites, particularly Cubesats. These "secondary payloads" don't get to dictate their final orbit (nor much else, really), but they do get into space. NASA's Cubesat Launch Initiative aims to offer up this capacity to non-commercial organizations.

NASA's, and indeed the industry's, medium-term approach has been to push more onus onto commercial launch providers, who can build rockets faster and cheaper than governments can. Orbital Sciences and SpaceX are actively showing that corporations can build large, capable rockets, and in the process are building confidence in this fledgling economy. Commercial is clearly the way to go for micro-launchers too. A cheap, small, rapidly deployable launch vehicle would be able to respond to small-satellite customers' fast development timeline and would allow them to launch to optimal orbits. A number of new companies have realized this, and push on with their plans to meet this demand.

In the longer-term more exotic launch systems may enter this market. For example, NASA is funding research into directed millimeter wave and laser beam systems, which can heat propellants to much higher temperatures than chemical combustion, to propel small single stage rockets into low Earth orbit.[8] In this case the heavy, complex and expensive power source is left on the ground and the power is beamed to the launcher.

Living in Congested Space using Space Traffic Management

Combining distributed small satellites and cheap launchers provides a redundant and resilient space infrastructure. If an asset is destroyed by a collision it could easily be replaced. While this is superior to the old paradigm of huge multi-purpose satellites, where months or years would be needed for a replacement, it is does not solve the underlying problem of an increasingly congested space. In fact, the small satellite approach might worsen the situation.

With each collision, the number of debris fragments increases and with it the risk of collisions increases again. Replacements will have to be launched more rapidly, bringing more mass into already congested orbits and fueling the runaway debris cascade. Without tackling the underlying problem by preventing collisions, this race will be a race against ourselves, finally to be lost. Congested orbits should be managed similarly to congested airspace, with Space Traffic Management.

Space Traffic Management (STM) is a multi-faceted game. In the past, the term has been used mostly to refer to the allocation of satellite orbits (and trying to manage this process proactively). As the debris environment worsens for the foreseeable future, STM will have to broaden to include improved space situational awareness, space collision avoidance, and the active management of space debris.

Effective STM requires effective space traffic knowledge, most of which is generated through networks of space surveillance sensors, predominantly the U.S. Air Force Space Surveillance System (the VHF "space fence"). There are currently about 17,000 tracked objects, but future plans for improved sensors (including debris laser ranging and a proposed S-band upgrade to the space fence) would raise the number of tracked objects to about 200,000 - many of which are still large enough be lethal to a satellite or manned space mission.

Most concepts to remediate the debris environment suffer from the same drawbacks as classic satellite operations; they require vastly expensive and singular missions. They aim to physically grab and de-orbit the worst potential debris sources: large, heavy objects.[9] Large objects are more likely to collide, and heavy objects cause larger fragmentation clouds. Removing these objects will reduce the overall probability of future collisions. Of course, this assumes no accidental collisions or explosions happen during the rather risky rendezvous, retrieve, and remove ballet.

Simulations show that, on average, five massive objects would have to be removed per year to stabilize predicted debris growth.[10] Such active removal missions would have a considerable project life cycle and so would not be useful for preventing imminent collisions. The active removal of mass may well be necessary, but it is also a game of statistics. The 2007 Fengyun-1C ASAT test and the 2009 Iridium-33, Kosmos-2251 collision have highlighted the sensitivity of the near-Earth environment to single catastrophic events. Even if five massive objects were fastidiously removed every year, there still remains the unlucky possibility of a single large collision rendering all of the good work of the previous years useless. Removing mass from orbit improves the debris environment, but does not enable actual case by case collision avoidance.

ASAT weapons can create a new kind of fall-out: a vast debris cloud that endangers the near-Earth operating environment for everyone.

Not only are ASAT weapons frowned upon by the arms control community and others who are interested in the safety of early warning systems and (nuclear) stability, but kinetic ASAT weapons can create a new kind of fallout: a vast debris cloud that endangers the near-Earth operating environment for everyone, for decades or longer. As such, they appear to only be considered weapons of last resort by the major space-faring nations. Deploying any active removal system, whether ground- or space-based, would effectively introduce a new class of "debris-conscious" ASAT weapons that are more usable because they would not endanger the aggressor's own satellites. Is there a way out of this bind? Perhaps...

Some of the technical and security challenges of space debris management might be resolved using an idea we are exploring at NASA Ames Research Center. The idea employs only photon pressure to slightly nudge space objects to prevent imminent collisions just before they are expected to happen. One has only to slightly (millimeters per second) change the velocity of one of the objects to cause it to arrive at the would-be accident location a fraction of a second earlier/later. At 7.5 km/s velocities, that fraction of a second relates to real displacements. Using a 1.5 meter-class telescope, a 10 kilowatt industrial laser, and adaptive optics to compensate for turbulence, the system would apply an intensity of the order of a few solar constants (bright sunlight) on targets in low Earth orbit.

Our calculations [11] have shown that the resulting photon pressure is sufficient to influence the orbits of a significant amount of debris in LEO. The effect is cumulative, so building up a network of ground stations would expand the efficacy.

Such a network could have multiple applications including debris laser ranging, debris characterization, providing an alternative to expensive collision avoidance

maneuvers, protecting non-propulsive satellites from collisions, preventing debris-debris collisions, performing satellite station keeping and enabling formation flying for small satellites.

The ASAT threat of such a system is negligible. The comparably low power of each single ground station would prohibit applications aiming to do structural damage. Sensors looking directly into the beam might be dazzled or blinded, but the same methods that protect sensors from inadvertent exposure to direct sunlight would be sufficient to prevent permanent damage. Causing collisions using this system is also not feasible: one would need to achieve meter-accuracies in those maneuvers to have a chance of causing a collision, which is orders of magnitude more accurate than the available orbital predictions. Indeed it is much harder to hit a small, and quickly moving, point in space than to hit anywhere outside that point. This system is much less of an arms control concern than any of the active debris removal schemes. It requires only that photons be launched into space and is therefore cheaper and less risky.

The drawbacks are the need for more planning and coordination, possibly involving multiple ground stations around the world, and the fact that it would be an ongoing space traffic management effort, rather than a remediation.

Lessons learned from a long history of air traffic management and satellite operations in geostationary orbit can be applied to low Earth orbit, particularly sun-synchronous orbit. Studies have shown that relatively simple slot allocation rules would allow much more efficient use of these orbits.[12] As more operators vie for space in dense orbital regimes we are going to need to leverage this accumulated knowledge, even without the paradigm shift to smaller satellites. Clearly defining these "rules of the road" is important to secure owner/operator cooperation and also to avoid misunderstandings in the security arena. Among these definitions should be safe passing distances and the assignment of responsibility for taking evasive action. For this to be achievable, paths of communication have to be clear and access to space situational awareness data must be universal and transparent.

Conclusion

We are facing a dilemma where the space environment is growing more congested and dangerous, but where the current approach does not deploy highly redundant and resilient systems. This results from the traditional focus on huge, expensive, multi-purpose satellites and the resulting need for large launch vehicles. We present a vision for the future, based on current trends and ongoing research that combines small satellites with off-the-shelf components, cheap micro-launchers and effective space traffic management. This paradigm shift promotes robust capabilities, preserves stability in the new space security environment, and may indeed set the stage for a smartphone-like app revolution in the space economy. ■

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