The Myth of the Tactical Satellite

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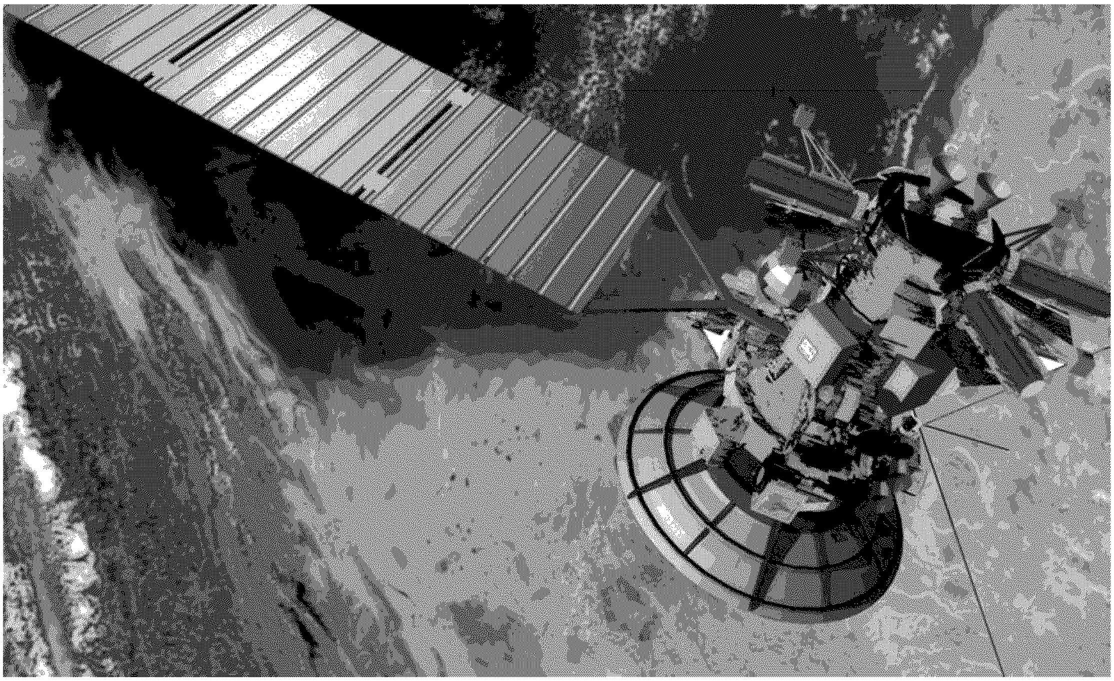
Editor's Note: This article is derived from a much more detailed, fully documented paper entitled "The Strategic Nature of Tactical Satellites" *available at the Web site of Maxwell Air Force Base's Airpower Research Institute: https://research.maxwell.af.mil/papers/ay2006/CADRE/tomme.pdf. While this article discusses the case of a single optimized low Earth orbit, the longer paper demonstrates that the results discussed here are quite general. It details the optimization technique and its underlying assumptions, discusses sensor limitations in depth, and debunks common arguments against the study methodology.*

Editorial Abstract: Many current proponents insist that "tactical" satellites are a must-have asset since they give the tactical war fighter a significant, palpable advantage in the battlespace. Colonel Tomme, however, argues that developing, funding, and producing these satellites constitute misdirected attempts to convince field commanders that satellite capabilities exist for battlefield exploitation. The author suggests that these proponents need to shift their focus toward the strategic realm, where measurable satellite effects can be meaningfully realized.



The wise are not wise because they make no mistakes. They are wise because they correct their mistakes as soon as they recognize them.

—Orson Scott Card
Xenocide, 1991

THE CONCEPT OF operationally responsive launch to get tactically useful payloads into orbit quickly and cheaply has been around for many years.[1] Operationally responsive launch has yet to be realized but is much closer to reality. There is a definite need for a capability to place inexpensive payloads into space on a very short time schedule.

Developing *tactically* useful payloads that can take advantage of responsive launch, however, is a different matter. A combination of *physical constraints* placed on satellites by orbital mechanics and *operational requirements* placed on their payloads by the missions that can be performed from space prevents all but the most rudimentary tactical missions from being attainable for the foreseeable future. Even if these missions can be performed from space, they will end up costing hundreds of thousands to several million dollars per hour overhead, a cost that would seem to place them beyond the reach of tactical or even theater commanders. Continued funding of the tactical satellite program under the misguided notion that such satellites can provide tactical effects on the ground only serves to drain scarce budgetary resources from other programs that *can* provide the desired effects.

The myth of tactical satellites is that they are tactical. As currently envisioned, there is no mission where a tactical satellite can provide primarily tactical effects.[2] To use computer programming language, "tactical" is a reserved word. When one uses that word to sell a program to a warrior, the warrior has a very specific understanding of what that technical term means—applying to small-scale, short-lived events, usually involving troops in contact.

The ability to launch small payloads into orbit on an operationally responsive timescale, however, does have its utility. The tactical satellite program needs a change of name and a change of focus, as the effects it can provide lie much closer to the strategic end of the spectrum of conflict. Such a change of focus would allow operationally responsive launch to compete in the *strategic* arena where it actually has a great deal of utility. In this case, however, tactical satellites appear to be a round peg in a square hole—a solution being forced into a mission where there are much better answers.

Background

The following table summarizes the optimized number of satellite passes, pass durations, and gap times for one reasonable circular

Table. Contact time and cost data for a 500 km circular orbit over Baghdad

Mission	*500 km Circular Orbit*				
	Average Number of Passes per Day	Average Pass Duration	Average Gap between Passes	Average Percent Useful Time Overhead (Duty Cycle)	Cost per Hour Overhead
	SINGLE SATELLITE				
Signals Intelligence (SIGINT)	9.7	7 min. 47 sec.	2 hr. 20 min.	5.6	$ 43K
Communications/ Blue Force Tracking (Comm/BFT)	8.7	6 min. 12 sec.	2 hr. 39 min.	3.9	61K
Imagery	4.6	1 min. 40 sec.	5 hr. 10 min.	0.5	429K
	FIVE-BALL CONSTELLATION				
SIGINT	48.6	7 min. 47 sec.	28 min.	27.8	43K
Comm/BFT	43.5	6 min. 12 sec.	32 min.	19.4	61K
Imagery	23.0	1 min. 40 sec.	1 hr. 02 min.	2.7	429K

Note: The hourly cost for a single satellite and a constellation of satellites is the same in this table due to the fact that adding a second satellite doubles both the coverage time and cost.

orbit altitude, chosen because it is about as high as any funded tactical satellite Advanced Concept Technology Demonstration (ACTD) is designed to orbit.[3] The parameters used to generate these results define the *tactical satellite program* as that term is used in this article.[4] The goal acquisition price per satellite and booster is no more than $20 million each.[5] They are designed to last between six months and one year to reduce the construction costs.[6] Again, I have not assumed numbers that will lead to a predetermined solution that will not support tactical satellites; these numbers are those espoused by tactical satellite proponents.

As can be seen from the table, signals intelligence (SIGINT) and communications/blue force tracking (comm/BFT) missions get significantly better performance than imagery missions. This difference is due to the severely constrained field of regard (FOR) available to imagery missions. Figure 1 shows the relative FORs, the area on the ground that its sensors

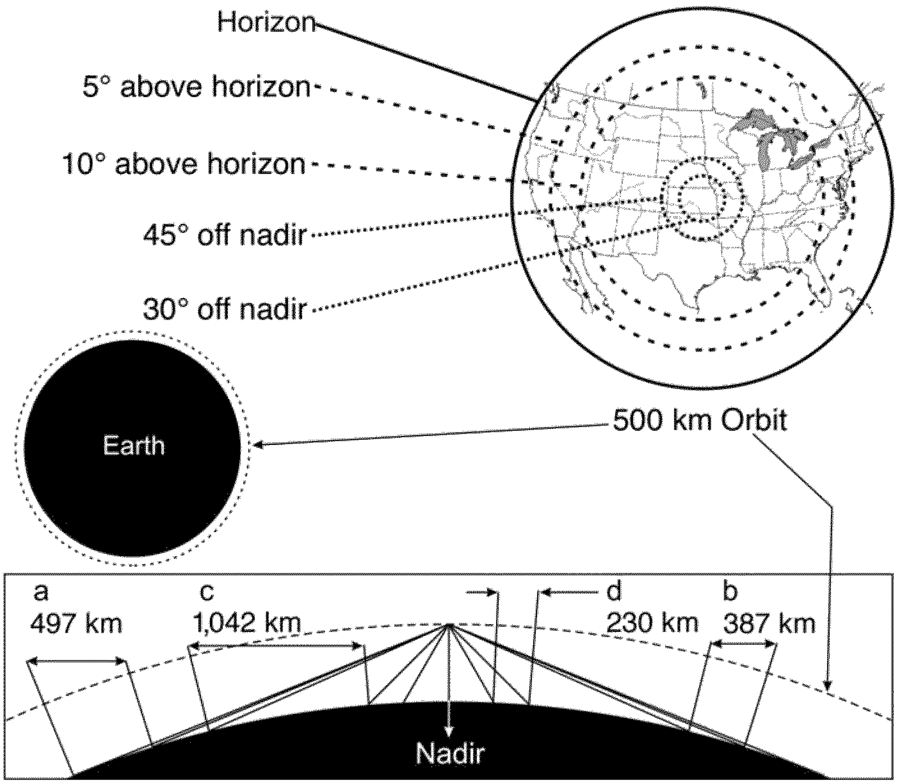


Figure 1. Fields of regard from 500 km. While it may appear at first glance that there are two points of view expressed in this figure (the ground-based point of view, above the horizon, and the satellite-based point of view, off nadir), the terms actually describe the same information. For any given altitude, any satellite-based FOR can be converted into a ground-based angle and vice versa. The conversion is a complicated function that depends upon satellite altitude. The two terms used are the ones commonly used operationally for the different mission types.

Note: In the upper portion of the figure, the dotted lines represent imagery-related FORs, the dashed lines represent comm/BFT-related FORs, and the solid line represents the SIGINT-related FORs. The middle-left portion shows the earth and a 500 km orbit to scale. The lower portion shows an enlarged side view of the FORs for the 500 km orbit. The distance labeled "a" is the difference between the radius of the horizon FOR and the five degrees above horizon FOR; b: between five and 10 degrees above the horizon FORs; c: between 10 degrees above horizon and 45 degrees off-nadir FORs; d: between 45 and 30 degrees off-nadir FORs.

can use, available to a satellite in a 500-kilometer (km) circular orbit—higher orbits would have similarly proportioned but larger FORs.[7] It should be obvious to any tactical war fighter that the levels of coverage shown in the table are inadequate for tactical needs. A tactical war fighter needs persistent imagery. Getting a snapshot every hour or so is not very useful at the tactical level, where the timescale of the action is measured in minutes or seconds.

SIGINT and comm/BFT missions are similarly ineffective from low Earth orbit (LEO) circular orbits. It is almost inconceivable to contemplate sending commanders into combat after telling them that they would only be able to communicate five minutes out of every half hour. A larger network similar to the 66 satellites in the Iridium constellation can provide good coverage, but even at a relatively inexpensive $20 million per satellite per year, the expense of such a network exceeds the reach of the tactical commander.[8]

In this article I will present the tactical satellite program in the best light possible. *I will assume that the satellites will work perfectly; they can be placed at will in the desired, optimized orbits; they will meet cost and lifetime goals; and the assumptions made about FORs will be as generous as possible. I will also assume perfect environmental conditions so the onboard sensors will always be able to perform their SIGINT, imagery, communications, and BFT missions. The goal is to show that even when all systems work better than advertised, the tactical satellite program still fails to provide tactical effects on the ground.* These generous programmatic assumptions will demonstrate that the failure to provide effects is not due to engineering shortfalls, where more money might solve the problem, but is due to physical limitations that cannot be overcome until the satellites become inexpensive enough to field constellations of hundreds simultaneously. By postulating the existence of a perfectly working technological product, we can then concentrate on evaluating the operational-utility part of the problem.

What is meant by a "perfectly working technological product" is a point worthy of discussion. From various briefings and published articles attributed to tactical satellite proponents, the goals of the generalized tactical satellite program appear to be to launch the energy equivalent of a 1,000-pound payload into a 100-nautical-mile (185 km) circular orbit.[9] Furthermore, the program seeks to keep it there for six months to a year at an acquisition cost of about $20 million per satellite and booster combined.[10] The results in the table assumed the use of an optimized orbit designed to give the maximum time for the satellite overhead, or *contact time.*[11] By optimizing the contact time, we also maximize the average number of satellite passes per day, maximize pass duration, minimize the amount of time the satellite is *not* overhead or *gap time,* and minimize the cost per hour overhead. These orbits are not necessarily the ones that are used operationally, as those orbits may be optimized for different constraints such as a constant-solar-illumination angle. However, these orbits give the absolute best cases for time and cost; all other orbits will necessarily give less time and will cost more per hour overhead.

Physical Constraints on Orbiting Objects

There are a number of "truisms" associated with orbits. They are presented here without proof. First, to optimize contact time, the inclination of the orbit should be very close to the latitude of the target. Second, increasing the orbital altitude increases the contact time.[12] This result is due to two causes. One can see farther when one gets higher.[13] Increasing altitude physically increases the size of the FOR, which in turn has a positive effect on contact time. Additionally, moving to a higher orbit slows the satellite down a bit, more closely matching its speed with that of the earth's rotation. The FOR thus moves more slowly across a target, also tending to increase the contact time. Finally, it is a truism that targets near the equator and the poles receive better optimized coverage than midlatitude targets.

As discussed above, a tactical satellite's orbital parameters will be limited by the energy that can be supplied by the booster. A booster that can put a 1,000-pound payload into a 185 km circular orbit could also put a 500-pound payload into a highly elliptical orbit with a perigee of 500 km and an apogee of 8,000 km.[14] If properly oriented, such a "magic orbit" will overfly the same point on the earth once per day and can provide a huge, slowly moving FOR during parts of its orbit, resulting in hours per day of coverage instead of mere minutes.[15]

We now have a good idea of how to optimize a satellite's circular orbit to obtain the maximum contact time over a specified target—put it as high as possible and match its inclination to the desired target's latitude. To optimize a magic orbit, we only need to make sure it is oriented properly in space using a specific set of orbital parameters. For the remainder of this article, I will assume the use of orbits optimized to maximize contact time. *This assumption will further ensure that we examine the operational utility of the tactical satellite concept in the best possible light: a platform that perfectly meets program goals and has been launched into an orbit that gives it the best chance for tactical success.*

Sensor Constraints on Optimized Orbits

As shown in figure 1, there are a number of FORs that can be applied to a satellite in any orbit. These FORs are based on the designed mission of the satellite. It would be nice to be able to use the huge horizon FOR all the time, but it is actually valid only for a few SIGINT missions. For other SIGINT missions as well as for the communications, BFT, and imagery missions, it is not. The reason the horizon FOR is not generally valid is due to sensor requirements. For SIGINT, communications, and BFT missions, the emitter of the signal being detected must have an unobstructed line of sight (LOS) to the sensor on the satellite.

SIGINT sensors can take in and analyze any signal they can detect. Thus, there is generally no requirement for them to be a certain angle above the horizon. If the terrain is flat and they can see all the way to the horizon, great. If there are mountains in the way, the sensor simply waits until it establishes LOS to the emitter and then begins collecting. For these reasons, I assume the horizon FOR is valid for most SIGINT missions.

Communications, BFT, and imagery missions are different. They cannot use the horizon FOR. Tactical comm/BFT capability has to be there all the time. Comm/BFT providers typically require their platforms to be at least five degrees above the horizon, with 10 degrees being more commonplace. While this requirement does not guarantee coverage in the bottom of a deep canyon, it does ensure that the odd tree, house, or hill will not normally interfere with direct LOS to the platform. As seen in figure 1, restricting the FOR to five degrees above the horizon has a significant effect on the performance delivered by an optimized orbit.

Imagery sensors are even more tightly constrained. Not only must they have LOS like the other missions, but they cannot look too far away from the vertical (nadir) without introducing a host of problems. These problems include foreshortening, excessive atmospheric degradation, and decreased resolution that can make analysis exceedingly difficult, if not impossible. Additionally, many imagery sensors operate in the visible-light region. It is extremely difficult for these sensors to function at night. Even night-capable infrared sensors have a hard time penetrating significant cloud cover.

Figure 2 shows the end result of the combination of orbital and sensor constraints for all latitudes on tactical satellites in 500 km orbits optimized to maximize contact time. Choosing any other orbit to achieve required mission goals will necessarily decrease coverage and increase cost.

The results in the table and figure 2 ignore the nontrivial limitations of weather and darkness and present optimized numbers that reflect an ability for imagery sensors to operate at full capability 24 hours a day/seven days a week (24/7); this assumption significantly overstates the actual capability.

The Operational Utility of Optimized Tactical Satellites

It is now time to examine space missions and compare the requirements placed on sat-

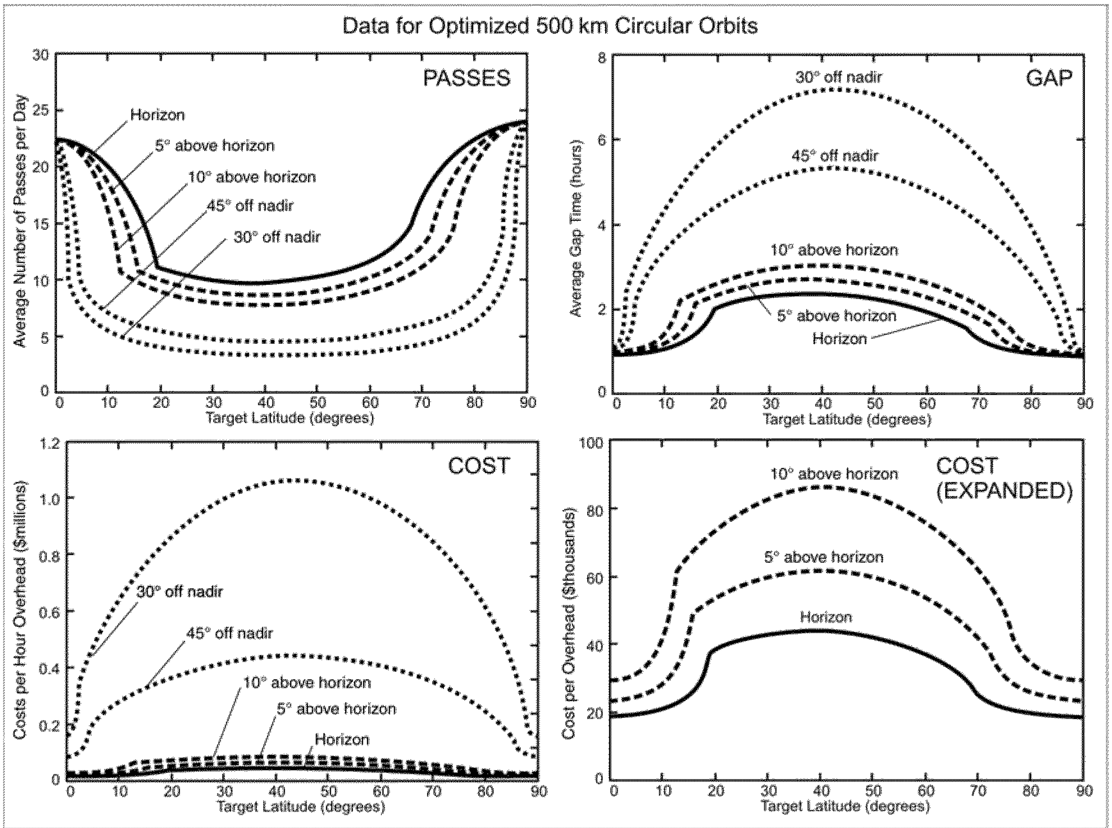


Figure 2. Number of passes, average gap time, and cost data for a tactical satellite in a 500 km orbit.

Note: The curves represent data for three mission types: SIGINT (solid), comm/BFT (dashed), and imagery (dotted). Cost data are shown in two panes as the scales between imagery and the other missions are quite disparate.

ellites with the constraints we have studied to this point. US joint space doctrine spells out four primary space mission areas: space force application, space support, space control, and space force enhancement.[16] Space force application consists of attacks against terrestrial targets by systems operating from or through space. Space support is the mission area that involves cradle-to-grave support of on-orbit assets. Space control ensures friendly use of space while denying it to adversaries and includes both offensive and defensive measures. Space force enhancement multiplies joint force effectiveness through heightened battlespace awareness. It includes the functions of intelligence, surveillance, and reconnaissance (ISR); tactical warning and attack assessment; environmental monitoring; communications; and precision navigation and timing. In this section of the study I will attempt to find niches in these mission areas for which tactical satellites are suited.

Space force application is not affected by the preceding discussion of orbital optimization, as no orbiting weapons are currently foreseen for the tactical satellite program. The *mass* of weapons such as lasers that could have an effect on the planet's surface would be much greater than the 1,000-pound tactical satellite reference mass. Conventional intercontinental ballistic missiles could possibly provide force-application effects within the weight range of the tactical satellite booster, but they are not satellites and will not be discussed in this article.

Likewise, space support is not a mission that has been discussed in the literature as a mission for tactical satellites. Space support from such things as launch facilities, operations centers, and the space communications and control network will be required for constellations of tactical satellites, but it will not provide a tactical effect to warriors on the ground. Tactical satellites will require space support but will not provide it. Note that I do not include the cost of any of this required space support in my cost calculations, as it is at present a relative unknown compared to the postulated $20 million per booster and satellite quoted by tactical satellite proponents.

Space control certainly seems to be within the purview of the reference energy (orbit/mass combination) of the tactical satellite program. Being able to responsively launch a satellite with the capability to maneuver in close proximity to other satellites would be a boon to those tasked with exercising both lethal and nonlethal shutter control on the space capabilities of hostile nations. However, such control is unquestionably a strategic mission with immense political ramifications and global effects. Employing it may provide advantage to tactical war fighters on the ground—many strategic actions do—but the advantage will be indirect. Thus, space control from a responsive launch platform will not be discussed further, since we are concerned with providing tactical effects on the ground.

After examining and eliminating the first three space missions from consideration, one sees that the only remaining space mission for which tactical satellites appear most useful is space force enhancement, the traditional role of most satellites. In fact, this mission appears to be the only one discussed to any degree in the literature dealing with tactical satellites. We will examine each of the five subelements of space force enhancement individually below, using the circular LEO and magic orbits discussed previously as baseline points of reference.

The tactical warning and attack assessment mission deals with providing timely notification of enemy use of ballistic missiles and nuclear detonations to the president and secretary of defense. This mission is currently performed from geosynchronous Earth orbit (GEO) by platforms such as the handful of Defense Support Program (DSP) satellites.[17] Such a mission would certainly be impossible from LEO without a constellation of hundreds of satellites, as it would require continual monitoring of the entire globe. While tactical satellites in magic orbits could conceivably perform the mission, it would still take between 12 and 20 of them to provide continual global coverage, at an acquisition cost of at least $240–400 million per year—a cost comparable to a single DSP bird, which is designed to last much longer. The mission is also undeniably strategic.

The environmental-monitoring mission provides data on space and terrestrial weather that could affect military operations. The Defense Meteorological Satellite Program (DMSP) platforms are one part of the current implementation of this mission element.[18] Tactical war fighters rely heavily on DMSP information to help plan their actions. Likewise, execution of the precision navigation and timing space mission element through the global positioning system (GPS) gives war fighters an enormous edge on the battlefield. GPS birds orbit much higher at about 11,000 km, making an orbit about every 12 hours.[19] Both systems are unarguably strategic, though, and replacement would not be the job of a small number of tactical assets. Additionally, were the DMSP or GPS constellations knocked out of service by some hostile act, it is difficult to imagine a situation where constellations replenished by responsively launched assets would be any less vulnerable to whatever brought the original systems down.

In contrast to the three subelements just discussed, the ISR and communications mission subelements do appear to have a need for tactical enhancement. Unfortunately, the cost-performance constraints of any responsive-launch boosters envisioned in the foreseeable future make tactical satellites poorly suited to be the source of that enhancement. I will discuss these constraints first in relation to circular LEO and then magic orbits.

The primary limitation to all tactical satellite applications from LEO is the very rapid passes of a relatively small FOR. LEO satellites do not and cannot provide persistence, an effect of paramount importance to warriors on the ground. This limitation is a severe constraint even for the best-case horizon FOR. From the truisms discussed above, it is obvious that to mitigate the rapid FOR pass, one should move to a higher altitude. However, there are drawbacks to this solution in addition to the reduction of payload mass in the energy trade for extra altitude.

While increasing the contact time and reducing the cost per hour overhead, raising the altitude has a negative impact on signal strength. Using the basic $1/r^2$ law for the attenuation of an electromagnetic signal, one sees that increasing altitude enough to significantly affect the FOR pass rate even more significantly decreases the signal strength received by the satellite.[20]

Large antennae for reception of radio signals can be manufactured relatively easily, and they are a relatively low-mass portion of the payload. To double the signal-collecting ability of an antenna, it is only necessary to double the antenna *area*, so compensating for the decreased signal strengths in most LEO orbits does not require an insurmountable increase in mass. The actual antenna sizes depend upon the required received signal strength, which is highly variable. Thus, it appears technically doable to put optics and antennae in LEO on tactical satellites.

That said, it remains for us to determine whether the effects provided by satellites in these LEO orbits are valuable to a tactical war fighter. The primary factors involved are, in decreasing order of importance to tactical warriors, coverage opportunities, coverage time, and cost. *To be truly useful to a tactical war fighter, effects have to be felt inside of the decision cycle of the enemy.* Information must be provided rapidly enough that it can influence the next friendly move before the enemy has time to readjust.[21] The table clearly shows that even at the 500 km altitude over Baghdad, the gap times are much longer than the timescale of a tactical engagement.

To get 24/7 persistence from even a SIGINT mission at 500 km would take a constellation of about 80 satellites.[22] It is quite evident that even at the relatively inexpensive projected cost of tactical satellites and their projected lifetimes that these numbers make persistent tactical satellite presence unaffordable. The acquisition cost of such a system would be at least *$1.6 billion each year.* It is for just such reasons that tactical satellite proponents instead propose very limited constellations, usually of five or fewer satellites, to provide what they call "tailored persistence."[23] Such persistence is obviously stroboscopic at best, providing a flash of utility periodically with large gaps of blindness in between.

On the other hand, even the relatively sparse constellation of five satellites discussed above would make such enemy communications and movement blackouts extremely difficult to employ for their *strategic* operations—operations where the timescale is long compared to the revisit rate. In most foreseeable situations, it would appear to be counterproductive to stop operations this frequently. On the other hand, for tactical engagements where the timescale is measured in minutes or seconds, much shorter than the satellite revisit rate, the overhead information will likely be too late and too sporadic to be of much use to friendly forces. "Tactical" satellites thus employed in LEO for SIGINT and imagery applications appear to be much more useful for strategic missions.

The budgetary numbers associated with tactical satellites greatly exceed the costs of putting existing manned and unmanned aircraft or proposed lighter-than-air, near-space assets over the battlefield. The persistence that these nonorbital platforms provide could be truly tailored to the pace of the battle instead of giving pseudorandomly-timed stroboscopic flashes of insight.[24]

The above discussions deal with the SIGINT and imagery missions, where even the sparse information provided by a small constellation could be of some use. On the other hand, sparse constellations of satellites in LEO have no chance of providing a useful communications capability. During an engagement, communications are needed when the warrior needs them, not when they are available. The tail can't wag the dog. Sporadic, pseudorandomly-timed communications capabilities will not support a tactical mission. Tactical commanders need the information available to them when *they* need it, not when the sensor is available to give it to them.

Apparently, tactical satellite proponents devised the magic orbit to counter the LEO coverage problem I have just discussed. The relatively long hang times over the target mean that five or six satellites could conceivably provide the 24/7 persistence that is unaffordable from LEO. This solution attacks only one of the two constraints on getting tactical effects from space—orbital mechanics. By moving much further away from the earth in an attempt to slow down the satellite passes, this solution compounds the other constraint—the payload's ability to perform the mission.

Using the 500 km orbit as the baseline, one finds that the average magic orbit distance from the target is 17 times further than the LEO. As an example of a specific effect on payload performance that such an increase in range will have, to get a one-meter optical image of Baghdad from the average magic distance of 8,500 km would take at least a 5.1 meter optical aperture (the size of the large telescope mirror at Mount Palomar Observatory in California) instead of the 0.36 meters required from 500 km.[25] For this reason, it would seem impractical to use the magic orbit for conventional imagery applications.

Similarly, a communications or SIGINT antenna in a magic orbit would have to increase in size to be as sensitive to signals as its LEO counterpart. Satellite communications on the move is a highly desired capability in the field.[26] Many people are familiar with satellite phones with their simple, easy-to-use whip antennae. These phones are generally run through the 66-satellite Iridium system orbiting in LEO at about 780 km. Iridium satellites use a set of three 1.6 square-meter (m^2) antennae for reception.[27] Having the satellites so close to the earth in LEO is the reason that the phones can employ antennae that don't require precise pointing at and tracking of the rapidly moving satellites. At their average distance above the horizon, magic orbits are 11 times further than even the Iridium constellation. The signal reaching them from the ground would thus be at least 120 times weaker. Since weight is a huge factor in getting to these higher orbits, increasing the size of the antennae to about the required 200 m^2 does not seem feasible. Without significantly larger antennae on the satellite, the ability to use whip antennae on the ground becomes problematic and would most likely require the use of the familiar small dishes to increase signal strength.

However, the use of a high-gain dish antenna is even more difficult for communicating with satellites in magic orbits. As discussed previously, it is currently difficult and therefore operationally prohibitive for troops on the move to stop, set up a dish antenna, and point it toward the *stationary* communications satellites that currently exist. This difficulty is significantly compounded when a *moving* satellite in a magic orbit has to be found and tracked in the middle of a tactical engagement. In contrast to the soldier on the ground who needs to manually point his antenna, many unmanned aerial vehicles (UAV) are already controlled through satellite links. It seems feasible for these links to be through satellites in magic orbits. However, the severe environment inherent in this orbital regime will likely be the ultimate arbiter of success for any magic orbit solution.

The requirement for satellites in magic orbits to regularly traverse the inner Van Allen belt will call for some mitigating engineering design to ensure that the one-year goal lifetime can be met. This mitigation can come in one of two ways: by using radiation-hardened, space-qualified components or by adding additional shielding to protect the cheaper commercial off-the-shelf electronics. The first method will almost certainly cause the budgetary goals of the program to be exceeded. The second method will add significant weight to the system. Neither solution seems palatable.

It is a physical fact that the constraints imposed by orbital mechanics and those imposed by sensor limitations work contrary to each other. Choosing a higher orbit that slows down the satellite pass to improve persistence ends up requiring huge increases in payload physical size, mass, and cost in order to maintain the standard of performance. It is an interesting "Catch-22": put the satellite low enough that it's affordable, and it's only marginally useful due to limited pass times, but put it high enough to be useful, and it's no longer affordable except at the strategic level.

Even with the favorable assumptions I have used in this analysis, it is clear that the ability of tactical satellites to deliver tactical effects is severely limited. Less optimistic (and more realistic) assumptions would further tip the balance against the utility and suitability of tactical satellites for tactical applications. As I have shown, there are severe physical constraints on satellites in circular LEO and elliptical magic orbits that conflict with tactical mission requirements. It seems highly impractical, if not impossible, to perform tactically useful imagery, communications, SIGINT, and BFT missions within these constraints, especially if cost remains a consideration.

Conclusion

Tactical satellites as currently defined by proponents aren't tactical. Just having a tactically responsive launch rate, if achievable, doesn't make an asset tactical. Just being much cheaper than other orbital platforms does not make an asset tactical. To meet the program goals briefed by tactical satellite proponents to senior military leaders, a tactical asset must also provide tactically relevant effects on the ground on a timescale that is less than that of a tactical engagement.

All is not gloom and doom for the tactical satellite program. Many of its goals are extremely worthwhile and will definitely benefit the nation and its defense. Standardizing busses and developing plug-and-play payloads will do a great deal to bring the cost of space effects down to earth. Being able to launch responsively will have a huge impact on space control options available to the national leadership. Being able to provide very cheap augmentation to expensive, hard-to-reconfigure national assets would be a boon to strategic planners. Being able to cross-correlate information from GEO and LEO birds for short time periods will make many strategic analysts extremely happy. It's not the program that is bad; it's simply misdirected. By using the word "tactical," proponents lead warriors to make unsupportable assumptions about the program's actual capabilities. Their focus needs to shift toward the strategic where the effects they advertise are possible to achieve and are useful.

In the end, it is much more appropriate for mythical *tactical* satellites to compete for funding against other strategically oriented programs. When they compete with and win funding against programs that actually have the potential to serve warriors on the ground, they detract from Congress's intended budgetary goals. Continuing to fund tactical satellites out of budget lines intended directly to serve the tactical war fighter does a disservice to both the taxpayer and the warrior on the ground. ❑

Notes

1. For example, see Maj Richard A. Hand, Maj Bonnie Houchen, and Maj Lou Larson, eds., *Space Handbook: A War Fighter's Guide to Space*, vol. 1 (Maxwell AFB, AL: Air University Press, 1993).

2. Air Force Tactical Exploitation of National Capabilities has a mission of finding tactically relevant uses for national assets, including satellites. While many tactical uses for satellites are possible, the global nature of an orbit makes the primary mission of these satellites strategic. "Air power *can* be global in its reach and ability to impose effects on an opponent, whereas space power, by its very nature, can *only* be global." Benjamin S. Lambeth, *Mastering the Ultimate High Ground: Next Steps in the Military Uses of Space*, RAND report MR-1649 (Santa Monica, CA: RAND, 2003), 45.

3. "TacSat-2/RoadRunner Micro Satellite Fact Sheet," February 2006, http://www.vs.afrl.af.mil/FactSheets/RoadRunner.pdf (accessed 4 April 2006); and "SpaceX Selected for Responsive Space Launch Demonstration under DARPA FALCON Program," SpaceX Web Site, 20 September 2004, http://www.spacex.com/index.html?section=media&content=http%3A//www.spacex.com/press11.php (accessed 6 November 2005).

4. There is no all-encompassing "tactical satellite program"; instead, there are a number of research efforts being conducted by Air Force Space Command's Space and Missile Systems Center (AFSPC/SMC), the Air Force Research Laboratory (AFRL), the Defense Advanced Research Projects Agency (DARPA), and others. The goals and parameters quoted throughout this article are generalized numbers based on numerous sources cited below.

5. In 2004 the advertised baseline cost for a tactical satellite and launch was $15 million. DOD, *Operationally Responsive Space Experiment: TacSat-1*, US Government White Paper (Washington, DC: DOD Office of Force Transformation, 17 October 2003), 2. By early 2005, the price was being quoted as $20 million to $30 million. Andy Pasztor, "Pentagon Envisions Operations with Small Satellites," *Wall Street Journal*, 26 August 2005. The current TacSat 2 will cost at least $50 million, barring further problems. Col Pamela Stewart, AFSPC Directorate of Plans and Requirements, "Responsive Space Near-Term Plan" (briefing, Air Force Scientific Advisory Board, Colorado Springs, CO, 27 April 2004). See also Col Rex Kiziah, AFRL, "Joint Warfighting Space" (briefing, Schriever III War Game, Nellis AFB, NV, 8 February 2005); and "Joint Warfighting Space: Not (Just) an Idea, Not Yet a Program," *Inside the Pentagon*, 6 May 2004, 1.

6. Kiziah, "Joint Warfighting Space." See also T. Ryan Space et al., "Transforming National Security Space Payloads," Paper no. RS2-2004-2001 (Los Angeles: Proceedings of the Second Responsive Space Conference, American Institute of Aeronautics and Astronautics, 19–22 April 2004); and Maj Scott Cook, AFSPC Directorate of Plans and Requirements, "Tactical Satellite (TacSat)/Joint Warfighting Space (JWS) Demonstration Program" (briefing, Headquarters AFSPC, Peterson AFB, CO, 6 January 2005).

7. The results presented in the table are based on quite optimistic fields of regard for the different mission types: horizon for SIGINT, five degrees above the horizon for comm/BFT, and 45 degrees off nadir for imagery. The numbers become much less favorable when more realistic fields of regard are used (10 degrees above the horizon for communications and 30 degrees off nadir for imagery). Cost data are based on the full year of service and the $20 million acquisition cost only, without factoring in infrastructure, daily operations, or personnel costs. Information on how the numbers were derived and much more detailed orbital-optimization calculations are provided in the longer version of this article.

8. Iridium Satellite Web Site, 12 November 2005, http://www.iridium.com/.

9. A booster can supply a certain amount of energy to a satellite. That energy is a somewhat complicated combination of the satellite's altitude and mass. The boosters currently envisioned for the tactical satellite program, DARPA's FALCON and SpaceX's Falcon 1, both have the approximate capability to put 1,000 pounds in a 100-nautical-mile orbit. They can put lighter payloads into higher orbits as long as the combination of payload mass and orbital altitude is less than the energy available from the booster.

10. Kiziah, "Joint Warfighting Space"; and Capt Beth Stargardt, AFRL Space Vehicle Directorate, "Tactical Space Employment for Joint Warfare" (briefing, Joint Forces Command Joint Space Concept Development and Experimentation Workshop, Norfolk, VA, 31 March 2004).

11. Data for circular orbits computed by the author using equations derived in M. W. Lo, "The Long-Term Forecast of Station View Periods," *The Telecommunications and Data Acquisition Progress Report 42-118, April–June 1994* (Pasadena, CA: Jet Propulsion Laboratory, 15 August 1994), 1–13, http://tmo.jpl.nasa.gov/progress_report/42-118/118J.pdf (accessed September 2005); and M. W. Lo, *Applications of Ergodic Theory to Coverage Analysis*, Paper no. AAS 03-638 (Big Sky, MT: Proceedings of the AAS Astrodynamics Specialist Conference, August 2003).

12. This truism is actually only true to certain altitudes. At a height at which one can almost see an entire hemisphere, raising the altitude further only marginally increases contact time. Additionally, the absolute maximum contact time would occur when a geostationary satellite is in view; that contact time would be 24/7. Moving higher than geosynchronous Earth orbit actually decreases the contact time. Since we are dealing with tactical satellites in LEO for this study, though, these limitations on the truism don't come into play.

13. T. S. Kelso, "Basics of the Geostationary Orbit," *Satellite Times*, May 1998, http://celestrak.com/columns/v04n07/ (accessed July 2005). In fact, it is possible to *actually* see an entire hemisphere only from a point an infinite distance away. A satellite in geostationary orbit can see only about 42 percent of the globe and cannot see locations with latitudes higher than 81 degrees.

14. James R. Wertz, "Coverage, Responsiveness, and Accessibility for Various 'Responsive Orbits,'" Paper no. RS3-2005-2002 (Los Angeles: Proceedings of the Third Responsive Space Conference, American Institute of Aeronautics and Astronautics, 25–28 April 2005), http://www.responsivespace.com/Papers/RS3%5CSESSION%20PAPERS%5CSESSION%202%5C2001-WERTZ%5C2001P.pdf (accessed 8 November 2005).

15. Rich Tuttle, "Air Force Studies Unique Orbit for Projected Family of Small Sats," *NetDefense*, 11 March 2004.

16. Joint Publication (JP) 3-14, *Joint Doctrine for Space Operations*, 9 August 2002, ix–x, IV-5–IV-10, and A-1–E-4.

17. "Defense Support Program Satellite Fact Sheet," 26 October 2005, http://space.au.af.mil/factsheets/dsp.htm.

18. "Defense Meteorological Satellite Program Fact Sheet," 26 October 2005, http://space.au.af.mil/factsheets/dmsp.htm.

19. "Navstar Global Positioning System Fact Sheet," 26 October 2005, http://space.au.af.mil/factsheets/gps.htm.

20. Ideal electromagnetic waves propagate as spheres or angular sections of spheres. The π area of a sphere is $4\pi r^2/3$. As the energy contained at any particular wave front must remain constant over time, the intensity of the wave at any point on that wave front must decrease to counter the spherical increase in the wave-front area. Thus, as the wave-front area increases as r^2, the intensity must decrease as $1/r^2$.

21. John R. Boyd, "A Discourse on Winning and Losing," Air University Library document no. MU 43947, August 1987. Unpublished briefing notes and essays.

22. Byron Hays, *Responsive Space/Tactical Satellite Utility Analysis* (briefing, Brig Gen William Shelton, director of Plans and Policy, US Strategic Command, April 2004).

23. Kiziah, "Joint Warfighting Space."

24. Orbital passes are not actually randomly distributed; they are, in fact, quite well determined, especially when highly variable perturbations such as atmospheric drag are neglected. However, for most orbits, the pattern of repetition for the satellite passes is not easily discerned by the warrior on the ground. Unless the orbit has been specifically tailored to do so (and in which case the satellite will not be providing the optimized maximum coverage time), the warrior cannot say, for example, "I will get two passes a day—one at noon and one at midnight—for the next two weeks." The pattern of repetition is vastly more complicated than that. For this reason, I will use the term *pseudorandom* to describe the pattern of satellite passes over a spot on the earth.

25. The wavelength used for this calculation was 400 nanometers (middle of the visible region). Distances were based on the slant range from the satellite to the edge of the FOR. The actual optics required to achieve the stated resolutions would be larger, as the diffraction limit is based on theoretically perfect seeing conditions.

26. David Hardy, "TacSat Demo Status: Senior Leader Vector Check" (briefing, AFRL, Kirtland AFB, NM, 22 September 2004).

27. Visual Satellite Observer's Web Site, "Catch a *Flaring/Glinting Iridium" (updated 6 March 2002), http://satobs.org/iridium.html (accessed 26 October 2005).