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The Strategic Nature of the Tactical Satellite

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REVISED EDITION

Author’s Note on the Revised Edition

Three years after it was first published this paper stands almost as written. Lectures given and feedback received following its publication revealed a large number of people who did not fully understand the many contour plots. The primary change in this edition is that those plots have been revised to be less cluttered and to include a three-dimensional representation of the contours to help visualize the concepts they present. The text describing how to interpret these plots has also been revised.

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Title of Paper: The Strategic Nature of the Tactical Satellite

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Executive Summary

Tactical: dealing with smaller engagements, smaller in scope, effect, and duration.

- *Department of Defense Dictionary of Military and Associated Terms*

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 likely getting much closer to reality. Air Force Chief of Staff General John Jumper alluded to the need for ORS when he said, "Small satellites will have a play once we get past the paradigm of space launch being an episodic event."[2] 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 prevent all but the most rudimentary tactical missions from being attainable for the foreseeable future. Foreseeable tactical satellite capabilities mean that tactical requirements of persistence and coverage can only be filled by constellations of relatively large numbers of satellites. If these missions are carried out, they will cost hundreds of thousands to millions of dollars per hour in overhead, costs that would seem to be beyond the reach of tactical or even theater commanders.

Using General Jumper's metric of "effects on the ground," the difficulties in tactical satellites actually being tactical become apparent.[3] Continued funding of the tactical satellite program under the misguided notion that they can provide tactical effects on the ground only serves to drain scarce budgetary resources from other programs that could provide these desired effects. The myth of the tactical satellite is that they are tactical. No mission exists where a tactical satellite could provide primarily tactical effects.[4] In a computer programming language, "tactical" would be a reserved word. When one uses it 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.

Orbital assets can and do perform a huge number of operationally relevant missions. In this case, however, they appear to be a round peg in a square hole—a solution being forced into a mission where there are much better answers. In all likelihood, tactical satellite advocates do not intentionally misrepresent the tactical nature of their product. The misuse of the very specific term "tactical" appears to come from ignorance, not malice. However, before any additional funding is expended toward this concept, realistically achievable effects of tactical satellites should be carefully evaluated against the requirements of tactical warfighters. Warriors of the next few decades should not die needlessly because programs that actually had a chance of providing needed tactical effects were not available because the money that would have funded them went to the mythical tactical satellite.

Accordingly, this paper will present the tactical satellite program in the best light possible to show that even if all systems work better than advertised, the projected tactical satellite program still fails to provide required 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 instead is due to physical limitations that cannot be overcome until the satellites become inexpensive enough to field constellations of hundreds simultaneously.

As an example of how limited the effects from a tactical satellite can be, a 5-ball satellite constellation optimized to cover Baghdad from an altitude of 500 km can only deliver, on average, about five minutes of communications coverage every half-hour or a single two-minute imagery pass every hour. It should be obvious to any tactical warfighter that such levels of coverage are inadequate for their needs. A tactical warfighter needs persistent imagery and constant communications. Getting a snapshot or minutes of communications every hour or so is not very useful at the tactical level, where the time scale of the action is measured in minutes or seconds.

To get around the marginally useful coverage times provided from LEO, tactical satellite proponents propose using a highly elliptical "Magic Orbit" to give near-continuous coverage.[5] When at the useful part of its orbit, a satellite in a magic orbit is about 8000 km above the earth, over 16 times further than a likely 500 km circular tactical satellite orbit. At this distance, conventional imagery missions are ineffective due to resolution limitations.

At the current time one of the biggest limitations on tactical use of satellite communications is that the soldier must stop his vehicle and point a high-gain antenna toward the stationary satellite to get reception. The reason for this limitation is that communications satellites are very far away and the signals they emit are relatively weak. The signal from a satellite in a magic orbit would be about 20 times stronger, but instead of coming from a stationary communications satellite it now comes from a moving one. The soldier's problem is now compounded—he has to stop and acquire a satellite in a constantly changing location, adding one further complication to a problem he doesn't need in the middle of a battle.

Finally, the space environment in which a satellite in a magic orbit must operate is extremely hostile. According to three tactical satellite proponents, "It is not surprising that no traditional systems have ever flown in this regime: the radiation environment is extremely severe." [6] Traditional systems, ones that do not rely on small boosters, ones that use space-hardened electronics and shielding, ones that are not limited to a few hundred pounds of mass, avoid the magic region. It seems improbable that small satellites built on a shoestring would be able to do better.

Even if tactical satellites in LEO could provide tactically useful effects on the ground, a dubious assumption at best, they would end up costing tens of thousands to millions of dollars per hour overhead. The ability to launch small payloads into orbit on an operationally responsive timescale, however, does have its utility. The effects that such an ability could deliver, however, are almost exclusively strategic, and the strategic effects could be extremely useful.

The purpose of this paper is as much to educate the tactical satellite proponent on what the warfighter needs as it is to educate the warrior on what tactical satellites can offer. 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. As it stands, the money the program receives comes from money intended to support tactical warfighters on the ground, support it cannot provide.

Ed “Mel” Tomme

List of Assumptions

The following assumptions will be used in this paper to ensure that the results are biased in favor of the tactical satellite program. Cost and performance numbers used are the most optimistic available from briefings and writings of tactical satellite proponents. Other assumptions all overstate the actual capabilities of any possible tactical satellite.

For the purposes of this study, it will be assumed that:

- the science and engineering portion of the tactical satellite program will work perfectly
- perfect environmental conditions will exist (24 hours of daylight per day and perpetually cloudless skies) so the onboard sensors will always be able to perform their missions
- the program will meet all of the goals of being able to launch the advertised payload mass at will to the advertised altitude (any combination of mass and altitude that equates to the energy in 1000 lbs. at 100 NM) for the advertised cost ($20M) and keep it there for the advertised lifetime (1 yr)
- financial estimates will only use acquisition costs for the booster and satellite; the considerable infrastructure, operations, and exploitation costs will not be considered
- all quoted orbits will be optimized to maximize the amount of time over a specific tactical region, an optimization that will give the absolute best cases for the time and cost analyses of a satellite destined for control by a theater commander
- satellite FORs will be better than commonly attained by commercial and military assets already on orbit (horizon for SIGINT, 5 degrees above the horizon for comm/BFT, and 45 degrees off nadir for imagery)
- no sensor FOV limitations will be applied; every sensor can fully and continuously utilize the much larger satellite FOR
- energy models used to calculate the decrease in mass that the same booster could boost to a higher altitude will not include the mass of the stage required for orbital insertion
- calculations to determine the required number of satellites in a constellation to provide persistent coverage will use less stringent long-term averages instead of the worst-case scenarios that would actually need to be employed.

Taken together, these assumptions greatly overstate the capabilities of tactical satellites. It is extremely unlikely that any actual implementation of real tactical satellites will approach this assumed performance. Even with the following analysis based on such overtly optimistic assumptions, this study will clearly demonstrate the inability of tactical satellites to provide effects that are of use to a tactical warrior.

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Section 1

Introduction

This paper is divided into several sections. As stated in the Executive Summary, physical limitations on satellite orbits and physical limitations on satellite sensors will play a large role in this analysis of the tactical effectiveness of tactical satellites. A fairly substantial amount of space will be devoted to showing how optimal orbits can be achieved, both for the circular and elliptical orbital regimes proposed by tactical satellite proponents. This paper will also examine how the fields of regard for various spacecraft sensors further limit the effectiveness of satellite contributions. This discussion will be somewhat technical, but is required to understand the full story behind the promise of tactical satellites. Finally, these physical satellite limitations will be discussed in the context of limitations to tactical effectiveness as judged by potential contributions to warfighters on the ground.

As mentioned above, tactical satellites require a combination of successful engineering and practical operational utility to prove themselves worthy of further funding. The engineering part of the problem is currently being worked by hundreds if not thousands of people from such organizations as the AFRL, the AFSPC's SMC, and other organizations including the Navy and Army. There are at least six TacSat demonstrations in various stages of funding, planning, and construction.[7] These demonstrations appear to be precursors to a more generalized tactical satellite program with the goal of producing and storing a number of these operationally responsive satellites and boosters sufficient to allow on-demand launch of customized satellites in response to a COCOM's contingency needs.[8]

Whether the technology to accomplish the ACTD goals or even to accomplish the longer-term goals for the envisioned generalized tactical satellite program exists is not the purpose of this paper. The validity of those science projects will soon be demonstrated and nothing written here will have any effect on their success or failure. Instead, to best demonstrate the effects of physical constraints and operational requirements on the ability of tactical satellites to perform a tactical mission, this paper will assume that the science and engineering portion of the tactical satellite program will work perfectly and will achieve all of the goals of being able to launch the advertised payload mass at will to the advertised altitude for the advertised cost and keep it there for the advertised lifetime. The numbers for calculating these favorable conditions come from briefings presented by tactical satellite advocates. Perfect environmental conditions will also be assumed so the onboard sensors will always be able to perform their SIGINT, imagery, comm, and BFT missions regardless of weather or day/night conditions. 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 1000 lb. payload into a 100 NM (185 km) circular orbit and keep it there for between six months and a year for an acquisition cost of about $20 million per satellite and booster combined.[9] Again, these are the baseline goals for a generalized tactical satellite program; the mission goals of the various TacSat ACTDs are somewhat different.

As will be explained in more detail in the body of this paper, physics requires all satellites to move. Except for special cases well outside the parameters associated with tactical satellites, it is not possible to “park” a satellite over a spot on the ground to get persistent coverage. As will also be explained later, the FOR available to a satellite, the area on the ground that its sensors can see, depends on the mission and performance of the sensor. The combination of satellite motion and FOR combine to limit the useful amount of time a satellite is overhead.

The results presented below will thus assume the use of an optimized orbit designed to give the maximum time for the satellite overhead, or contact time. Contact time is the most important parameter for tactical warfighters, as it is the only time that the expensive satellite effects will be available to them. 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 (gap time), and minimize the cost per hour overhead.

Orbits optimized for maximum contact time are not necessarily the ones that are used operationally, as those orbits may be (correctly) optimized for different operational constraints such as a constant solar illumination angle. However, orbits optimized to maximize contact time give the absolute best cases for time and cost; all other orbits will necessarily give less time and will cost more per hour overhead. To provide a simplified baseline for the remainder of the paper, satellite capabilities over the specific target of Baghdad associated with two representative LEO orbits will be discussed up front. Tables 1 and 2 summarize the optimized number of satellite passes, pass durations, and gap times for two circular orbit altitudes. The parameters used to generate these results define the tactical satellite program as that term is used in this paper.[10]

The 100 NM orbital altitude is shown as it is the reference altitude for a generalized tactical satellite program.[11] (The way the altitude is frequently quoted in tactical satellite literature, 100 nm, is equal to 185 km. All other distances in this paper will be quoted in kilometers.) At that altitude, atmospheric drag would bring down a satellite without propulsion capability in a matter of days,[12] so it is obviously a non-player for an actual tactical satellite. This represents the approximate energy available from the two responsive launch boosters potentially available in the near-term for tactical satellite launches, DARPA’s FALCON and SpaceX’s Falcon 1.[13] Energy is a complicated function of altitude and payload mass. Generally you have to trade one of these parameters to get better performance from the other. Since the 100 NM orbit is too low for real tactical satellites, we have to give up some of the 1000 lb. payload mass to allow the orbit to move higher where drag will not be as significant a factor. Mass tradeoffs will be discussed in more depth later in this paper. The 500 km orbital altitude is shown as it is about as high as any funded TacSat ACTD is designed to orbit.[14]

Data for single satellites as well as for a 5-ball constellation are shown. The single satellite data are useful to determine baseline information. The 5-ball constellation information is shown since many briefings on tactical satellites use a variation of this implementation to increase coverage time.[15] By increasing the number of satellites, the number of passes is multiplied and the average gap between passes is essentially divided by the number of satellites in the constellation. The average pass duration and cost are unchanged since they depend on each satellite individually.[16] Note that the goal acquisition price per satellite and booster is now more than $20 million each and they are designed to last between six months and one year to keep the construction costs down by using COTS electronics.[17] Again, numbers that will lead to a predetermined solution that will not support tactical satellites have not been assumed. These numbers are those espoused by tactical satellite proponents. The definition of what a tactical satellite is comes from published numbers in the responsive space community.

Mission	100 NM (185 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					
SIGINT	8.3	4 min 29 sec	2 hr 48 min	2.7 percent	$88K
Comm/ BFT	7.0	3 min 8 sec	3 hr 22 min	1.6 percent	$150K
Imagery	3.0	33 sec	8 hr 01 min	0.1 percent	$2M
5-BALL CONSTELLATION					
SIGINT	41.8	4 min 29 sec	34 min	13.2 percent	$88K
Comm/ BFT	34.9	3 min 8 sec	40 min	7.8 percent	$150K
Imagery	14.9	33 sec	1 hr 36 min	0.6 percent	$2M

Table 1. Contact time and cost data for a 100 NM circular orbit over Baghdad.18

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					
SIGINT	9.7	7 min 47 sec	2 hr 20 min	5.6 percent	$43K
Comm/ BFT	8.7	6 min 12 sec	2 hr 39 min	3.9 percent	$61K
Imagery	4.6	1 min 40 sec	5 hr 10 min	0.5 percent	$429K
5-BALL CONSTELLATION					
SIGINT	48.6	7 min 47 sec	28 min	27.8 percent	$43K
Comm/ BFT	43.5	6 min 12 sec	32 min	19.4 percent	$61K
Imagery	23.0	1 min 40 sec	1 hr 02 min	2.7 percent	$429K

Table 2. Contact time and cost data for a 500 km circular orbit over Baghdad.

As can be seen from the tables, SIGINT and comm/BFT missions get significantly better performance than imagery missions. This difference is due to the severely constrained FORs available to imagery missions. As an example, a 5-ball SIGINT mission optimized to provide coverage over Baghdad at the tactical satellite reference altitude of 100 NM would provide about 4 ½ minutes of coverage out of every 38 minutes and would cost $88 thousand an hour overhead. A similarly optimized imagery mission would only provide about 30 seconds of coverage every hour and a half at a cost of at least $2 million per hour. Even when control of the satellite payload is actually delegated to tactical level, as is envisioned using the Air Force Space Battlelab's extremely innovative VMOC program,[19] the ability to be able to acquire and image more than one or two specific targets in the short time the satellite is overhead is technically ambitious. Thus, depending on one's priority for imagery, it could be many hours or days before the desired image is taken.

While boosting the satellite altitude to a more realistic 500 km increases contact time, it simultaneously degrades image resolution by a factor of almost three and signal strength for all missions (imagery, comm/BFT, and SIGINT) by a factor of over seven.[20] Overcoming these mission degradations involves adding larger sensors and associated equipment, increasing weight and making it that much more difficult to get the payload to the higher orbit.

Tactical SIGINT is equally problematic from tactical satellites. The signals can only be collected at best for seven minutes each half hour, giving spotty information about a dynamic battlefield. BFT and comm missions are similarly ineffective from LEO circular orbits. It is almost inconceivable to contemplate sending a commander into combat after telling him that he'd only be able to communicate across distances of more than about 10 km for 3 to 6 minutes out of every 30 or 40, the coverage time he would get with the sparse networks advertised by tactical satellite proponents. A large network similar to the 66 satellites in the Iridium constellation can provide good coverage, [21] but even at a relatively inexpensive $20 million per satellite the expense of such a network would put it out of reach of the tactical commander.

The following few sections of this paper will discuss in detail the limitations that physics puts on tactical satellites, first dealing with orbital mechanics and then with sensor performance, both in LEO and in magic orbits. The discussion will be somewhat technical but not to a level that is beyond an educated layman. There are a large number of claims made in this paper; these technical sections are where the proof of these claims is located. Should the reader's interest lie elsewhere, these sections can be skimmed. A less technical discussion of the conclusions reached from these data begins in the section entitled The Operational Utility of Optimized Tactical Satellites.

Section 2

Physical Constraints on Orbiting Objects

We will first look at some of the physical constraints imposed by the stated tactical satellite orbital parameters and will then attempt to optimize them to show how they could deliver improved performance. In order to understand these physical constraints we need to gain a rudimentary understanding of what makes satellites move.[22] Orbital mechanics is a topic that, while not difficult to understand, is not commonly understood by warriors. A basic concept that appears to be commonly misunderstood is that satellites cannot hover above a target, providing stay-and-stare persistence. All satellites must move to stay in orbit. If we drop a *stationary* satellite it will fall toward the center of the earth, *perpendicular* to the earth's surface, regardless of whether we drop it from two meters or from orbital altitudes. The only way a satellite can stay in orbit is for it to have some motion *parallel* to the earth's surface that keeps it from crashing into the planet since it is continually falling due to the part of its motion that is perpendicular to the surface. It can also be shown that the closer a satellite is to the earth, the faster it has to move to prevent such a crash. For most satellites very close to the earth in LEO, they must move so quickly that it takes them only about 90 minutes to circumnavigate the earth. [23]

It has been shown that all satellites must move in order to stay in orbit. That statement seems to contradict what many warriors believe they understand: there are some satellites that do not move. When they stop in the middle of a battle to set up a SATCOM link, they point to a specific spot in the sky and are certain to get a connection with a stationary satellite. In reality, these "stationary" satellites are moving, but they're moving at such a rate that it takes about 24 hours for them to go around the earth and the earth moves at the same rate beneath them. They only appear to be stationary to an earthbound observer. To an observer anywhere else, it is apparent that, like the earth itself, they really do move. Such satellites are in geostationary orbits,

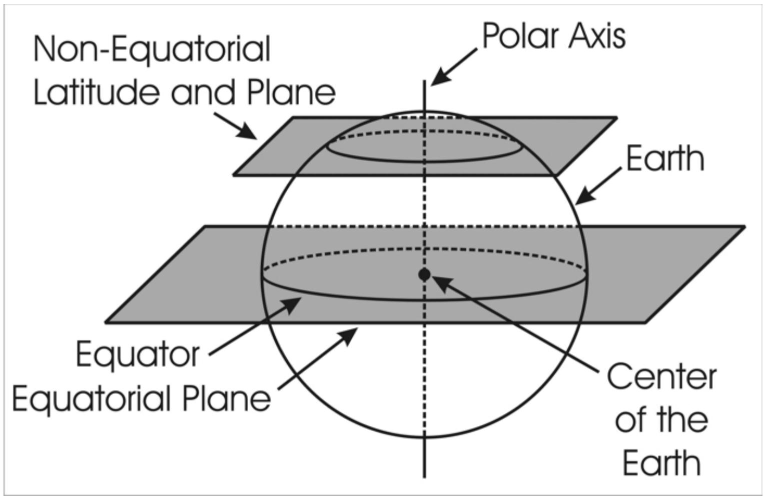

Figure 1. Allowable and Unallowable Orbits. The equatorial plane contains the center of the earth and can thus host an orbit. The plane containing any other line of latitude does not pass through the center of the earth and thus cannot support an orbit.

a special case of GEO. GEO satellites can only be placed in orbits 35,800 km above the earth, a huge distance equal to almost six times the earth's radius of 6,400 km. It takes a very large booster, lots of energy, and a great deal of money to put a payload into GEO. Additionally, sensors must be considerably larger, more sensitive, and more robust at GEO altitudes in order to sense the same parameters as sensors on a LEO satellite.

Another concept that is not commonly understood relates to the direction a satellite's motion has to take. All closed orbits are circles or ellipses, figures that can be drawn on a sheet of paper or any other plane. While most people understand that fact, a further constraint is that the plane of the orbit must also contain the center of the earth. This limitation means that satellites can only appear stationary if they are in geosynchronous equatorial orbits (the plane containing the equator also contains the center of the earth—Figure 1 illustrates this concept). A GEO satellite placed over the equator would thus appear to be stationary (a geostationary orbit), while a GEO satellite whose orbital plane is tilted with respect to the equatorial plane by an angle known as its orbital inclination would continue to take 24 hours to orbit but would cycle the latitude it is directly over between the northern and southern latitudes equal to its inclination once every day. Figure 2 depicts the concept of orbital inclination. Note that the inclined orbital plane also contains the center of the earth.

For the present, only satellite orbits that are circular will be discussed. Later we will examine what effect trying to put a satellite into an elliptical orbit will have on its tactical utility. The combination of a satellite's altitude and inclination are the two attributes that allow us to calculate how often a satellite will be over a specific target location. One final piece of information is needed, however, to allow us to know how much of its time overhead will actually be useful to us. That information is known as the satellite's FOR, sometimes referred to as its footprint. The FOR is the area on the ground that can be used for the mission the satellite is required to perform.[24] It should be apparent that FORs get bigger the higher the satellite orbits; think of how much further you can see from the top of a building than you can see from ground level.

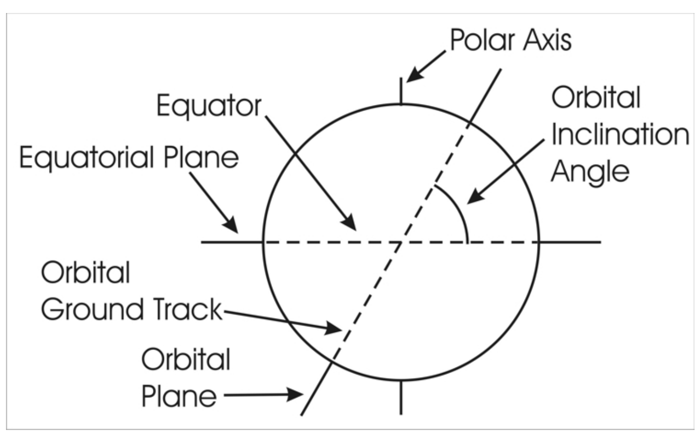

Figure 2. Depiction of the orbital inclination angle.

Fields of regard are mission driven. For example, the ground-based node of a ground-to-space comm/BFT link generally requires the space-based link to be a specified angle above the horizon, generally five to ten degrees, to ensure connectivity.[25] The field of regard for such a mission would be the area on the ground from where the satellite would be at or above the specified angle above the horizon. In contrast, a signals intelligence mission detecting radio transmissions only needs to have line of sight to the emitter it is trying to detect, so its field of regard extends to the horizon as seen from the satellite.[26]

Imagery satellites have much more restrictive FORs. In order to properly analyze overhead images, the images cannot be taken from too shallow an angle. If they are, foreshortening makes it very difficult to determine where objects are with respect to each other. It is also much more difficult to interpret what the images represent when the viewing angles are shallow; try to read this page from a point of view near the edge of the sheet and you'll see why:

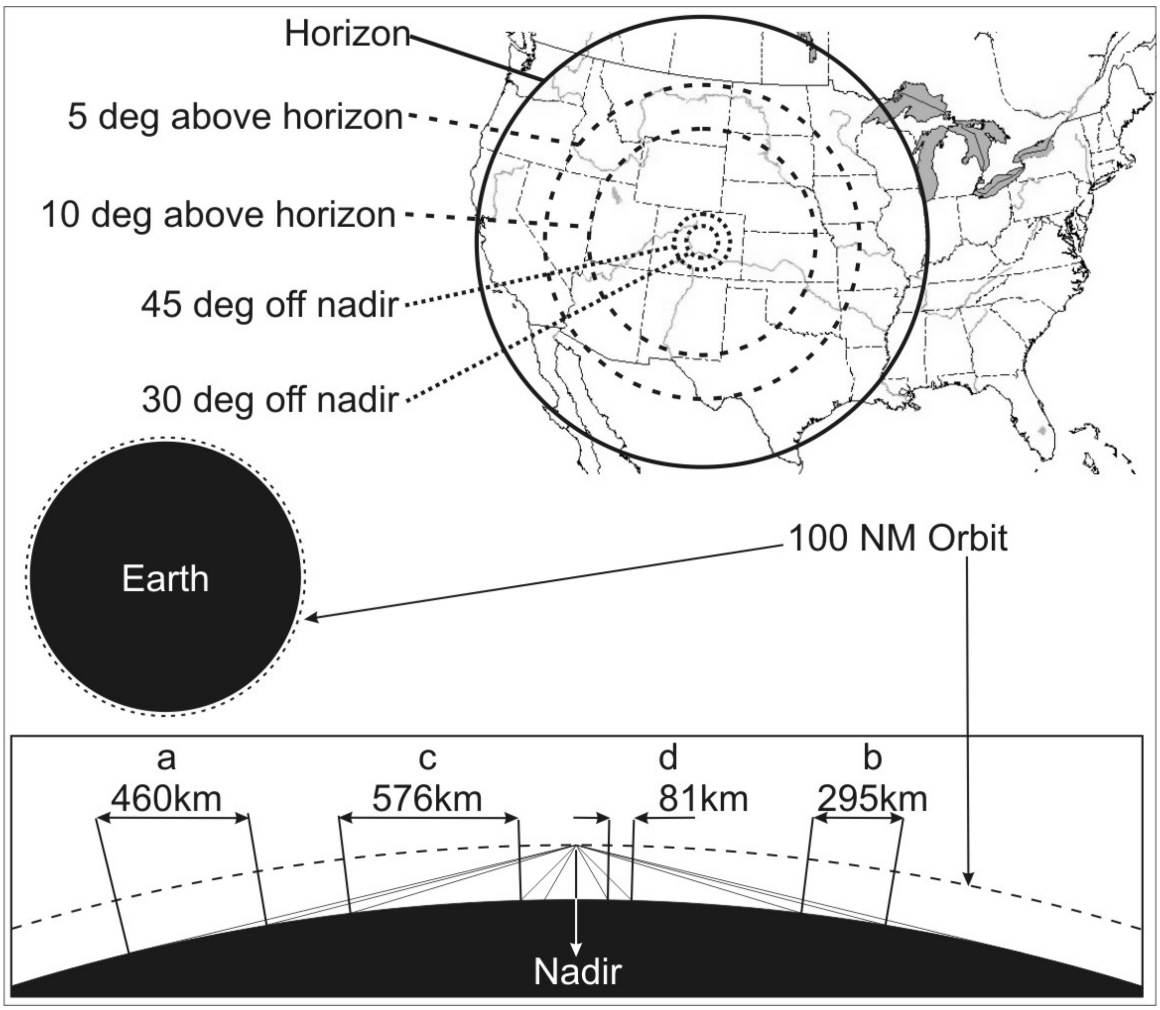

Figure 3. Fields of regard from 100NM. In the upper portion of the figure, the dotted lines represent imagery-related fields of regard, the dashed lines represent comm/BFT-related fields of regard, and the solid line represents the SIGINT-related field of regard. The middle left portion shows the earth and a 100NM orbit to scale. The lower portion shows an enlarged side view of the fields of regard for the 100NM orbit. The distance labeled "a" is the difference between the radius of the horizon field of regard and the 5 deg above horizon field of regard; b: between 5 and 10 degrees above the horizon fields of regard; c: between 10 degrees above horizon and 45 degrees off-nadir fields of regard; d: between 45 and 30 degrees off-nadir fields of regard.

the letters become so foreshortened as to become unreadable. Atmospheric effects are much more pronounced when the image is taken at a shallow angle due to the much greater distance through the atmosphere the light has to travel from the object. Finally, the resolution of an image, the ability to distinguish small, closely-spaced objects from each other, is directly related to how far away the object is.[27] The shallower the angle, the further away the objects being imaged and the poorer the resolution. At shallower than certain angles, the images become useless as the information desired (discriminating between tank and truck, for example) can no longer be obtained. For these and other reasons, imagery satellites seldom look more than about 30 degrees off-nadir, where nadir is the direction of an imaginary line extending from the satellite straight down toward the center of the earth.[28]

It must be noted that whether the requirement is ground-based (i.e., five degrees above

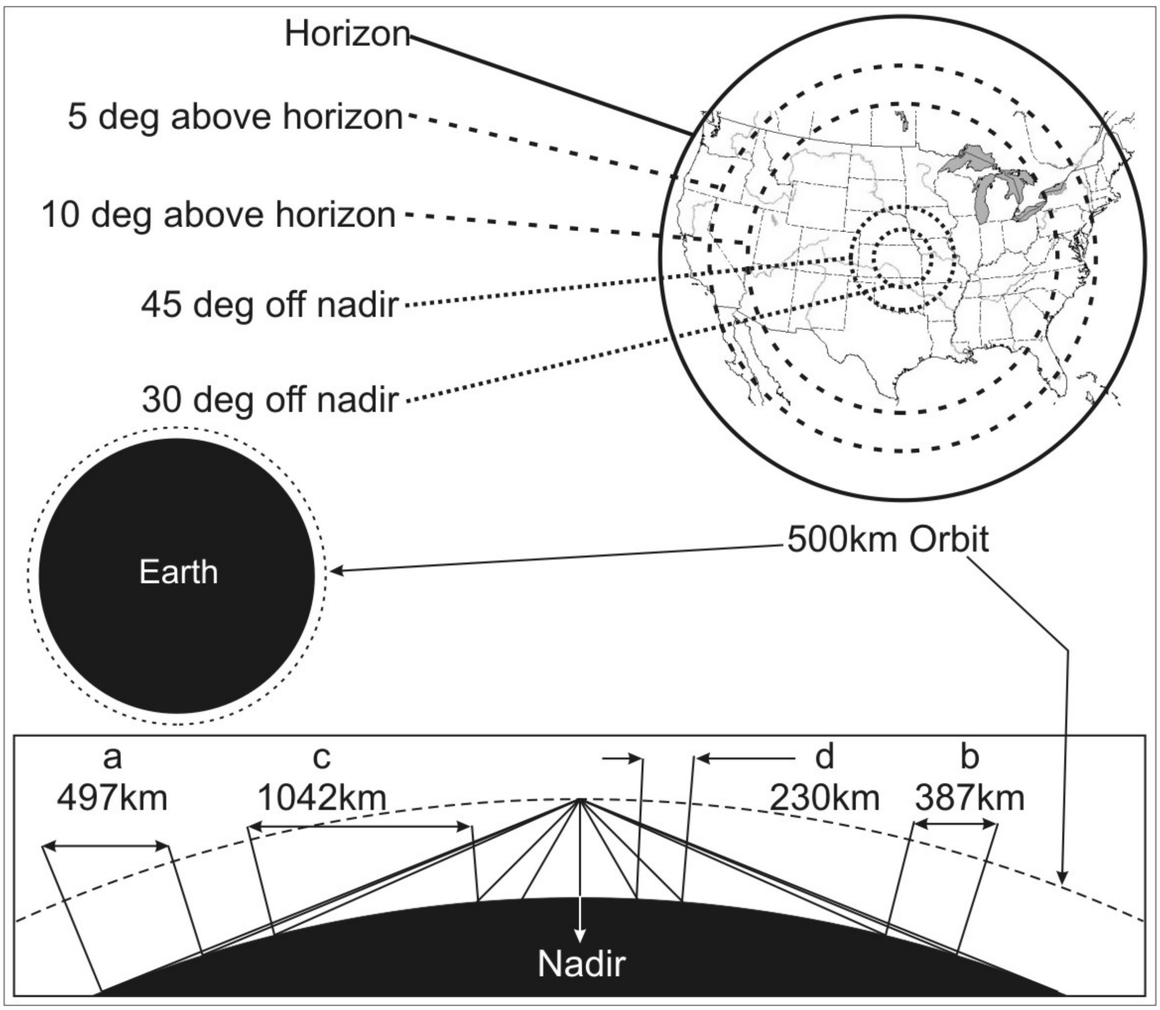

Figure 4. Fields of regard from 500km. In the upper portion of the figure, the dotted lines represent imagery-related fields of regard, the dashed lines represent comm/BFT-related fields of regard, and the solid line represents the SIGINT-related field of regard. The middle left portion shows the earth and a 500km orbit to scale. The lower portion shows an enlarged side view of the fields of regard for the 500km orbit. The distance labeled "a" is the difference between the radius of the horizon field of regard and the 5 deg above horizon field of regard; b: between 5 and 10 degrees above the horizon fields of regard; c: between 10 degrees above horizon and 45 degrees off-nadir fields of regard; d: between 45 and 30 degrees off-nadir fields of regard.

the horizon) or satellite-based (i.e., 45 degrees off-nadir), the FOR describes a specific circle on the ground. For any given altitude, any satellite-based FOR can be converted into a ground based angle and vice versa. Numerous figures will be shown later in this paper with data for multiple mission types on the same plot. Remembering that the angle label is just one of convenience based on the mission may simplify interpretation of these plots. As an example of this concept, Figure 3 and Figure 4 show the relative sizes of these mission-driven fields of regard for a satellite orbiting at 100NM and 500km, respectively. Other satellites in LEO would have FORs with similar radius ratios, but the entire group would be proportionately larger or smaller on the map depending on whether the orbit was higher or lower than those depicted. The first part of this paper will only consider the most favorable FOR, where the satellite can see all the way to the horizon. This approach will allow us to concentrate on the problem of orbital optimization with fewer distractions. Once that optimization problem is understood, the FORs will be restricted to examine their effects on target coverage by satellites.

It is also very important to realize that just because a target is in the FOR of the satellite, it is not necessarily being imaged by the payload. Satellites typically do not image their entire FOR during a single pass. Especially for the high resolution imagery necessary for the tactical warfighter, only a tiny fraction of the whole FOR can be seen by the camera's FOV at any one time. As part of the goal to discuss tactical satellites in the most favorable terms, the limitations of the sensor FOV have not been included in this study, but keep in mind that those limitations will severely limit the optimistic numbers presented in this paper.

Orbit Optimization to Maximize Contact Time

We're now to the point where we can start putting some of this seemingly esoteric knowledge about satellite orbits to good, practical use. The goal is to determine how to optimize a satellite orbit for a tactical application. Some time will be spent discussing orbital optimization as it is a key part of argument presented. In addition to assuming perfect programmatics for the discussion of tactical satellites, these hypothetical, perfectly operating satellites will be placed in orbits that give them the absolute best chance for success. "Optimization" would seem to imply that we would like just as much time overhead, or contact time, from the satellite as possible. "Tactical" tells us that we are interested in optimizing the orbit for a specific location, perhaps a city or a very small region of a country but most definitely not for continental or global coverage. Again, to give tactical satellites the maximum benefit of the doubt, the best-case scenario of a horizon FOR will be discussed. The absolute maximum contact times possible will be calculated using this largest-possible FOR. Remember, however, that FORs are mission-dependent, and most missions will not be able to take full advantage of a satellite's LOS to the horizon.

Ignoring sensor performance, we have four parameters at our disposal that actually make a difference: orbital altitude, orbital inclination, satellite FOR, and target location. If we plot the contact time a satellite would achieve from the combinations of these parameters we should be able to discern some trends on how to optimize our tactical orbit. For a generalized tactical optimization study, we are not interested in the exact day-to-day times that a particular satellite will be overhead. Instead, our true interest lies in the long-term average contact time with the satellite. Long-term averages also simplify our target location parameter as well, as the symmetry of the sphere of the earth means that we really only need to specify the latitude of the target; all longitudes crossing the specified latitude will have the same long-term average contact times.[29] Symmetry also implies that northern and southern latitudes will have the same long-term average contact times.

The accompanying charts (Figures 5 to 7) plot the average daily contact time a single satellite with a horizon FOR would have over three cities at different latitudes: Bogotá, Colombia (4 degrees north latitude); Baghdad, Iraq (33 degrees north latitude); and Oslo, Norway (60 degrees north latitude).[30] Discussions of constellations of satellites will come later. These cities were chosen to give representative samples of low, mid, and high latitude results.

While these plots may look intimidating, almost everyone in the military and a large fraction of the general population should actually have no trouble interpreting them as they are exactly like plots with which they are already familiar: topographical maps. On a topographical map, the x- and y-axes are longitude and latitude, respectively. The contour lines represent the height above sea level, with the contour lines connecting all heights that have the same value. When lines are far apart, the terrain is relatively flat; when they are close together the terrain is steep.

From contour plots like these you are able to visualize three dimensional information on a two dimensional map. If you want to find the altitude at a specific lat/long combination, all you do is find the appropriate longitude along the bottom of the map, follow it up until you cross the appropriate latitude, and note the location of the desired point with respect to the two nearest contour lines.

Using the contour plots in this paper is exactly the same. Note that in Figure 5 the x-axis is labeled satellite altitude and the y-axis is labeled satellite inclination. Instead of height above sea level as is plotted on a topographical map, the contours on these plots show the number of minutes contact time one would expect from a satellite at any combination of satellite altitude and inclination. For example, if for some reason we needed to know how long the contact time would be in Figure 5 for a satellite at 500 km with a 60-degree inclination, we would find 500 km. along the bottom of the plot, follow that value vertically up the plot until we were directly across from 60 deg. on the left side of the chart, and then read the value of a little less than 40 minutes from the contour.

Extending our topographical map analogy to look at the general features of the contours, it should be apparent that the contours in the top portion of the plot are pretty far apart, indicating that the region is relatively flat. What does *flat* mean with respect to these contours? It means that the contact time doesn't change very quickly in this region. Looking further down the plot, you should see a region where the contours become fairly closely spaced. Noting that as we move from top to bottom across this region the contour labels get larger, you should be able to visualize this region as analogous to a hill where the altitude is going up rapidly. This hill appears to peak at the bottom right corner of Figure 5. Remember, though, that in these plots the height of the hills is not altitude, but rather contact time. Thus, the contact time you could expect from your satellite would increase rapidly as you moved down and to the right on this chart, peaking at the bottom right corner.

To assist in visualizing these hills and valleys throughout the rest of this paper, a small three-dimensional color representation of the two-dimensional contour plot is included in each figure. These insets are color-coded similar to geographic maps, with blue being seas (at very low altitudes), green representing lower elevations, yellows and oranges representing medium altitudes, and white representing snow-capped peaks. Note that the color coding does not correspond to a given "altitude;" the code is scaled so that black is the lowest contact time in the

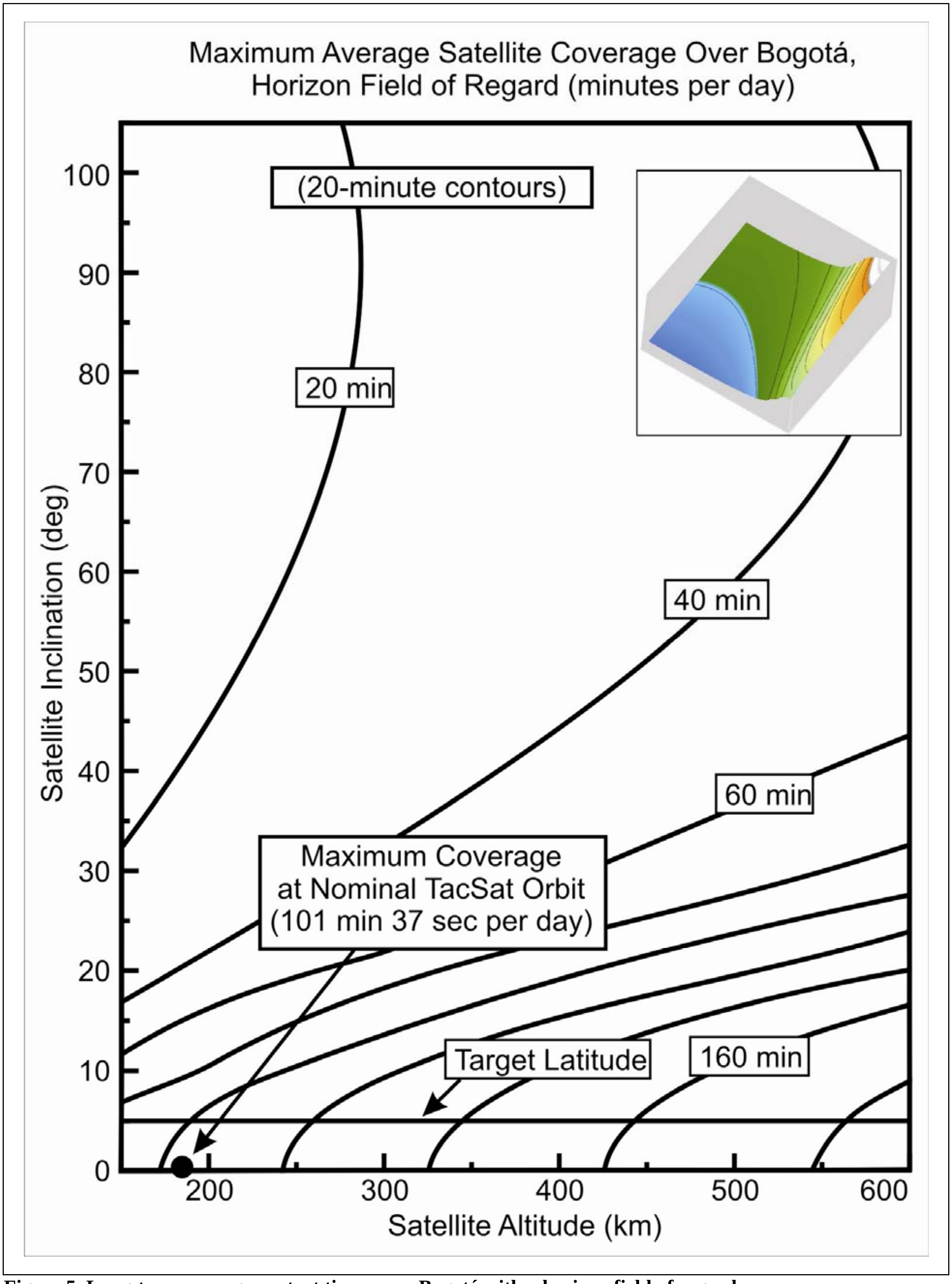

Figure 5. Long-term average contact times over <u>Bogotá</u> with a <u>horizon</u> field of regard.

plot and white is the highest. Black will almost always be zero while white can be anything from 2 to 200 minutes, depending on the range of values for the individual plot. In these next few figures, this three-dimensional plot is what the contour plot would look like if it had been rotated counter-clockwise by about 60 degrees and the top of the plot rotated away from you by about 45 degrees. A good exercise to ensure you understand these plots is to see if you can look at the contours as if you were reading a topographical map, visualize what the contours are telling you about the terrain, and then looking at the three-dimensional inset to confirm your mental image. Again, always remember that the height of the hills, valleys, and plains represent *contact time* in these plots, *not actual height* like on a topographical map.

As a brief aside, from our earlier discussion about how only four parameters are required to describe the long-term contact time for a satellite, it should be apparent that since we can only vary two at a time on a two-dimensional sheet of paper we must fix the other two. In this case, since we are varying altitude and inclination, the target location and sensor FOR must be fixed. You can confirm this fact by noting the title of the plots, showing that in the case of Figure 5 the target location is Bogotá and the FOR is all the way to the horizon.

Now that we have a better conceptual feel for what these charts are trying to tell us, let's look at some specifics. In these three figures altitudes are varied between 150 and 600 km; the lower limit being where the atmosphere becomes thick enough to bring a satellite down in a matter of several days and the upper limit being somewhat arbitrary but around the published value for the funded TacSat programs and substantially higher than the general tactical satellite altitude reference orbit of 100 NM (185 km). Inclinations are varied between zero degrees (equatorial orbits) and 105 degrees. The three plots are somewhat similar in shape, varying only in detail. They are approximately symmetrical about the horizontal 90 degree inclination line.[31]

There are black areas at the bottoms of the two higher-latitude plots (Baghdad and Oslo) showing the combination of inclinations and altitudes that provide no coverage of the targets in question. From Figure 2 it should make sense that a satellite with a shallow inclination angle and low altitude might never be able to see a target located at a high latitude. To give a more explicit example, Figure 8 shows a satellite ground trace for an orbital inclination of 15 degrees. The swaths centered along the ground trace show the approximate size for horizon FORs for several satellite altitudes. Note that all of the swaths cover Bogotá while none would ever allow Oslo to be imaged. The higher altitude (larger) swath would allow Baghdad to be imaged. These examples illustrate why the Oslo plot (Figure 7) has the largest black area, and also illustrates why the black areas become narrower at higher altitudes.

From all the contour plots in this paper it will become obvious that there is a certain orbital inclination that, for any given altitude, maximizes the contact time. As an example, let us say we are trying to maximize the contact time over Baghdad (Figure 6) at the tactical satellite reference altitude of 100 NM (185 km). We find 185 km along the bottom of Figure 6 and begin to move upward from zero inclination orbits to higher inclination orbits, noting the contact times as we go along. At first, we cross the black zone that indicates that a satellite at those low inclinations will never pass over Baghdad. The fact that there are no contours here means the terrain is absolutely flat.

Eventually we come to the point at about 22 degrees inclination where we make landfall and the terrain begins to rise rapidly. What's really happening here is that the satellite FOR circle begins to pass over its target city. The contact time is short, less than 20 minutes per day between

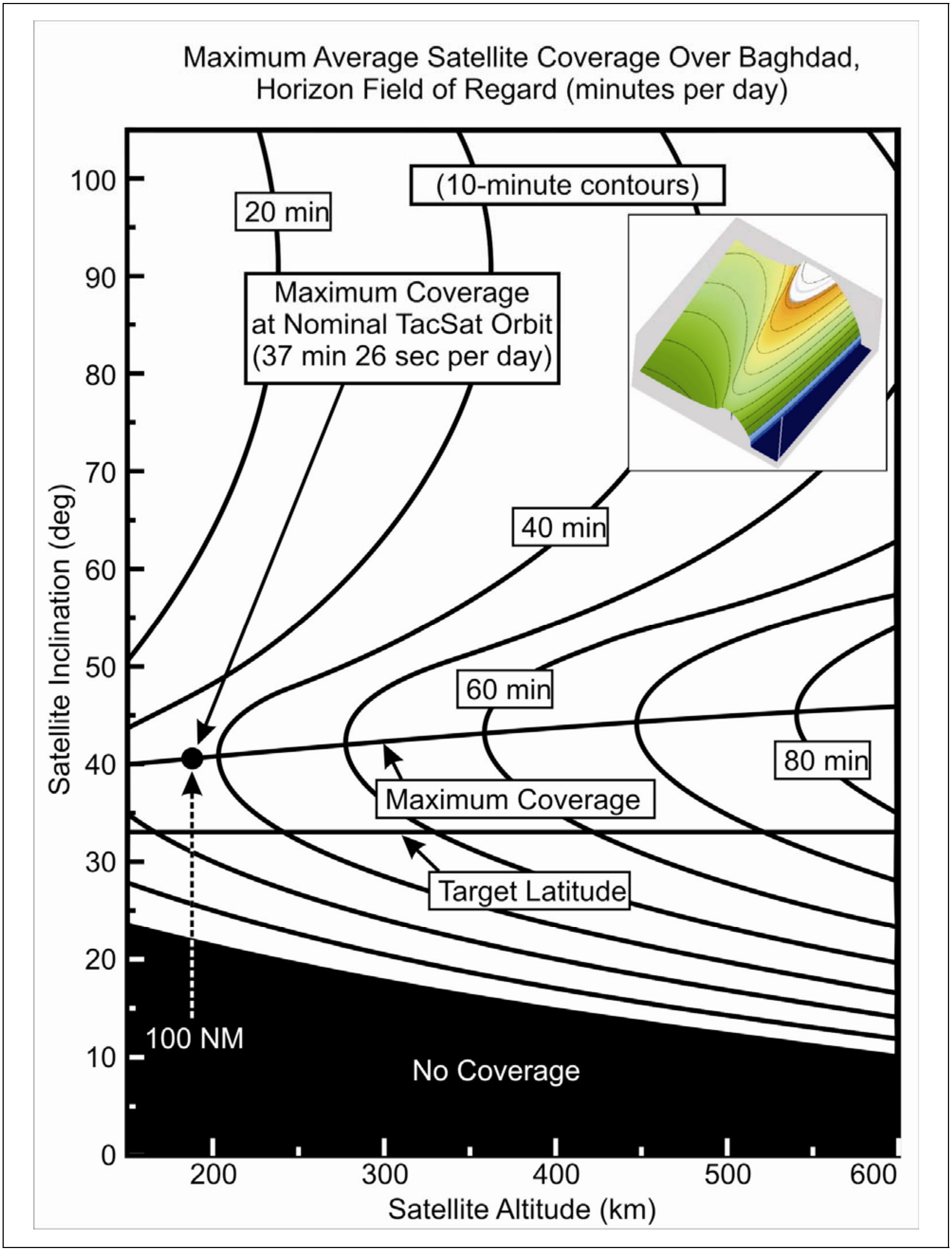

Figure 6. Long-term average contact times over <u>Baghdad</u> with a <u>horizon</u> field of regard.

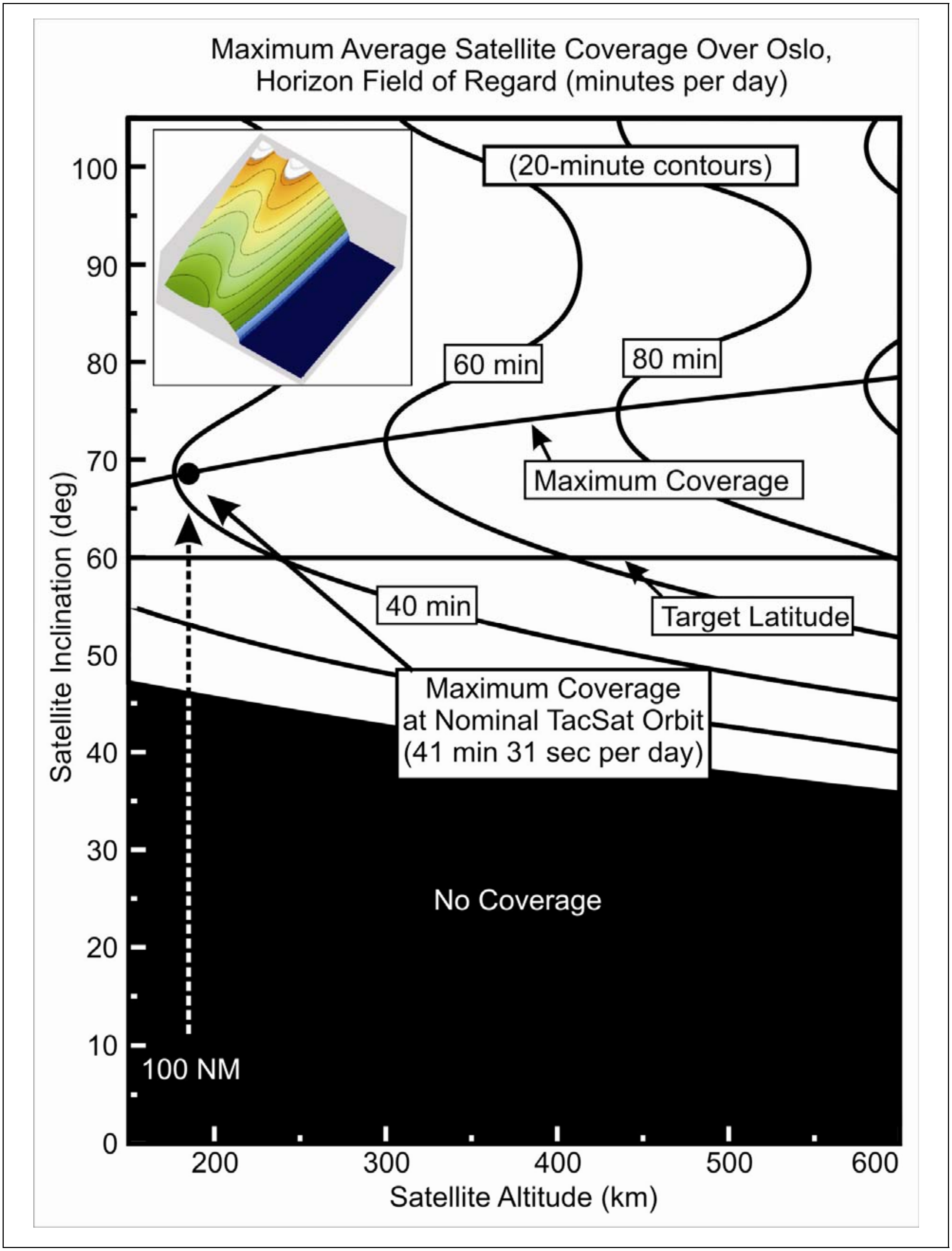

Figure 7. Long-term average contact times over <u>Oslo</u> with a <u>horizon</u> field of regard.

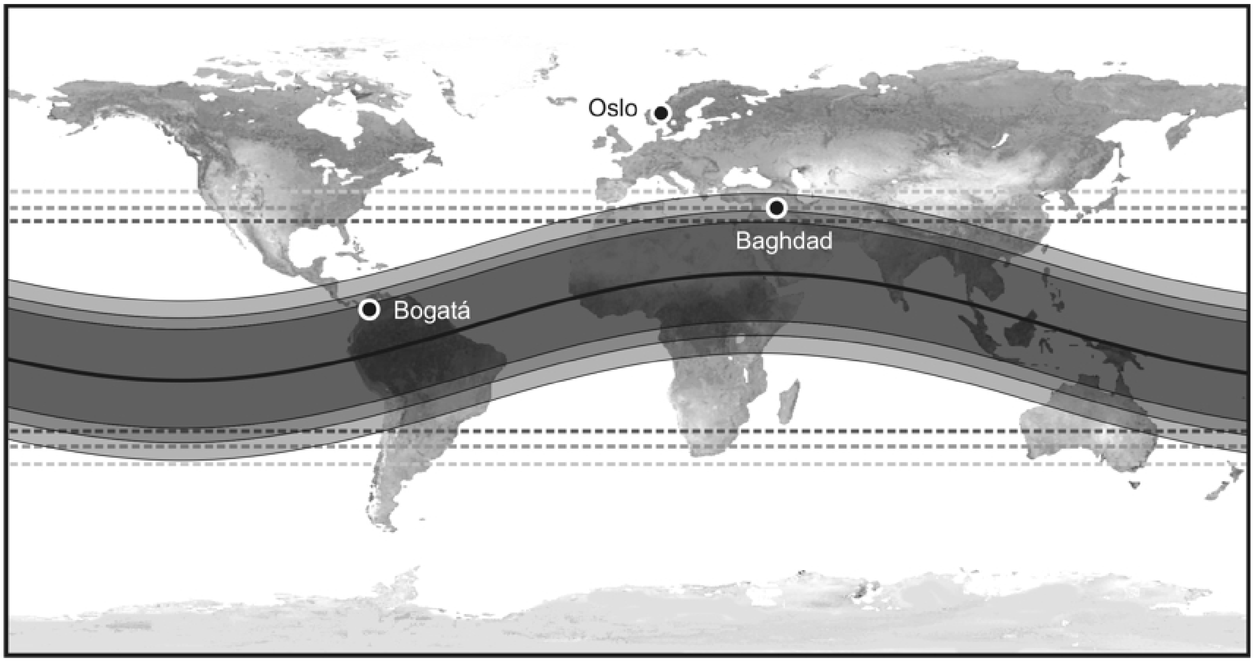

Figure 8. Satellite ground trace showing horizon fields of regard for a 15 degree inclination orbit from 100NM (185km; inner, darkest shaded region), 300km (middle shaded region), and 500km (outer, lightest shaded region). All points between the dotted lines corresponding to the peaks and troughs of the shaded regions would eventually be covered by the satellite.

the first two contours, but soon become longer and wider as we move further up the chart and wider portions of the FOR begin to pass over the city (this concept will be discussed later , but a quick peek at Figure 11 might be helpful now) .

If we continue further upward, the contact times begin to drop off again to below 30 then below 20 minutes per day. Obviously, we passed through the point at which the contact time was maximized for our choice of altitude and target. That point is indicated on the plot at about 41 degrees inclination, where the absolute maximum contact time for these conditions is about 37 minutes per day. The line of maximized contact time for any orbital altitude is shown on the chart for easy reference.

For the Bogotá plot the inclination that maximizes contact time is equatorial; for Oslo the approximate inclination is 68 degrees. Coincidentally, those inclinations are quite close to the cities' latitudes.[32] We have discovered our first truism for tactical satellites: to optimize contact time the inclination of the orbit should be very close to the latitude of the target. Also notice the unstated corollary: no satellite can be optimized for more than one target latitude.[33] The horizon FOR for these plots is the largest available to a satellite. It will be shown later that the smaller the FOR, the closer the optimal inclination is to the target's latitude and the more critical the optimal orbital inclination becomes to maximizing contact time.

Now that we have examined the effects of changing the satellite's inclination on contact times by moving vertically on the charts, let us look at what varying the altitude (moving horizontally) will do. Our second truism is immediately apparent from the plots: increasing the orbital altitude increases the contact time.[34] This result is due to two causes. As discussed earlier, you can see farther when you get higher.[35] Increasing your 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, the point of view of the plots will be changed a bit to demonstrate a third truism: targets near the equator and the poles receive better optimized coverage than mid-latitude targets. In fact, the optimized contact time is almost symmetrical about a target latitude of 45 degrees. With a bit of thought you can prove this truism to yourself. It is possible to put a satellite in orbit directly over the equator, since the plane of the equator contains the center of the earth. If your target is on the equator, the satellite will pass over it every time it goes around the earth. If your target is at mid-latitudes, even an optimized orbit will not necessarily pass over it every single time around the earth; depending upon the match between the satellite's and the earth's rotational speeds, sometimes the satellite will reach its maximum inclination over the target, at other times it will reach its maximum latitude some distance away from the target (see Figure 8 for an example). If your target is at one of the poles, you can put your satellite into a polar orbit with an inclination of 90 degrees. No matter what longitude along which the satellite makes its approach, it will still pass directly over the pole on every orbit.

The layout of these plots must be changed to demonstrate this truism. Instead of showing satellite *altitude* on the horizontal axis, Figures 9 and 10 show target *latitude*. Instead of a *fixed target location* as was used before, the *altitude is fixed* from plot to plot. There's nothing scary about this change. Remember the four parameters? We can always choose the two we want to vary as long as we fix the other two. As always, the height of the "hills" in these plots is still the contact time in minutes per day.

The lower right corner of the contour plot in Figure 9 is now the black, completely flat region where the satellite's inclination is too low to allow its FOR to pass over the high-latitude targets. The broad ridge running from the lower left to the upper right is the band of optimized inclinations. A dotted line indicating the exact location of the optimized inclination for each target latitude runs through the middle of that ridge, with a maximum value somewhere between 20 and 40 minutes per day, as indicated by the bounding contours. Note that it generally follows the inclination-equal-to-latitude truism discussed above. Once the inclination gets too high with respect to the latitude, coverage drops off as can be seen by the broad, flat plain in the upper left portion of the plot. Finally, the very high coverage numbers—up to two hours per day of contact time for the tactical satellite reference altitude—for optimized orbits near the equator and the poles are clearly visible. Note that for these plots the inset is rotated clockwise instead of counterclockwise as was the case with the previously shown inclination vs. altitude plots.

Also as discussed above, it is apparent from comparing Figures 9 and 10 that moving higher does improve contact time: moving from 185 km (100 nm) to 500 km gives about a factor of two increase in contact time across the board. Notice that the ridge gets broader and higher as altitude is increased when switching between the two plots. As tactical warfighters we generally do not get to choose the latitude of our targets to a great extent. Thus this inclination-latitude truism is less useful to us than the other two, but it is nevertheless an important fact.

<u>We now have a good idea of how to optimize a satellite's 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.</u> For the remainder of this study, the use of optimized orbits will be assumed. 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.

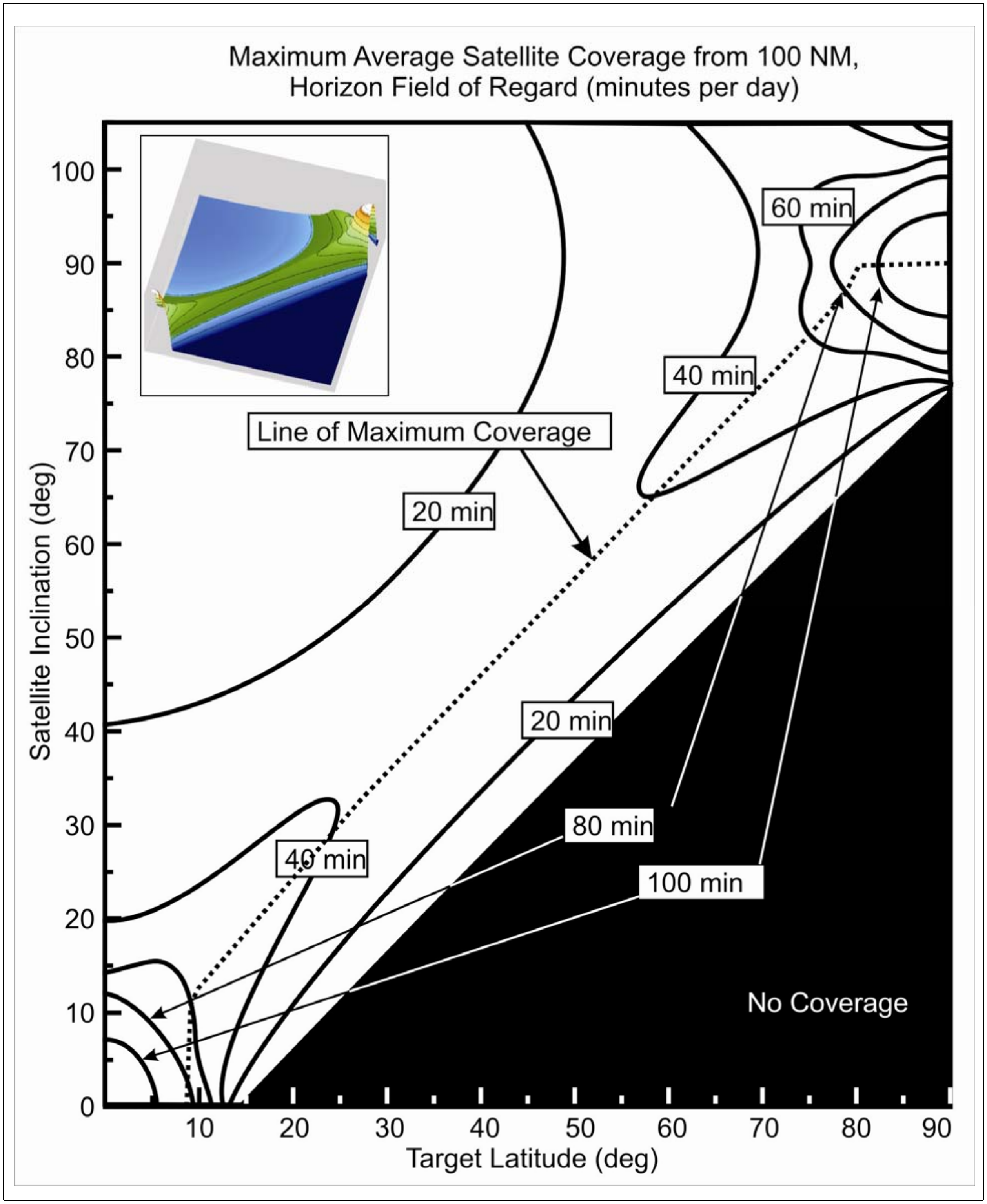

Figure 9. Horizon field of regard satellite coverage from 100NM (185km).

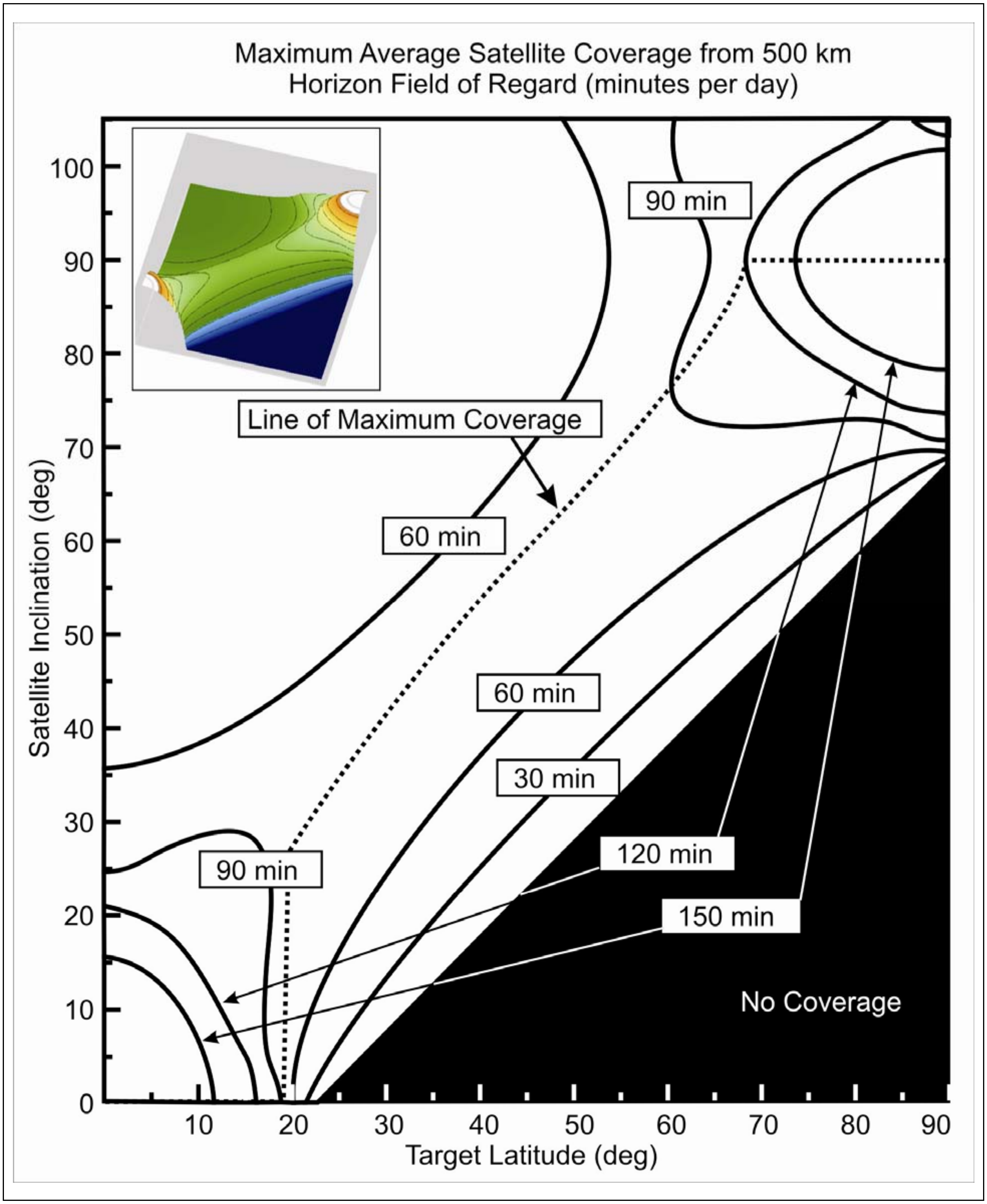

Figure 10. <u>Horizon</u> field of regard satellite coverage from <u>500km</u>.

Average Daily Contact Times, Pass Durations, and Coverage Gaps

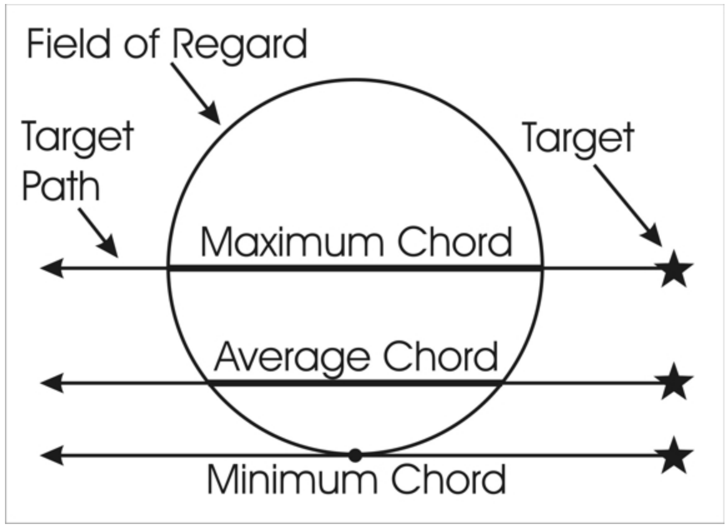

Figure 11. Three different target paths through a field of regard give three different transit lengths (pass durations).

Figures 5 to 7 (p. 10, ff) display the long-term average contact time per day for the specified combinations of inclination, altitude, target location, and FOR. For the general tactical satellite reference of a 100 NM orbit, the plots clearly show that the maximum contact time per day one could expect to achieve with a horizon FOR would be approximately 100 minutes for Bogotá, 37 minutes for Baghdad, and 42 minutes for Oslo. For the 500 km orbit, the maximum times at these locations would be approximately 170, 76, and 90 minutes. What the plots do not clearly show is how many passes per day, how long each pass would be, and how much of a gap in coverage exists between passes. It is fairly easy to calculate the exact contact times for a real-world satellite using any of a number of commercially-available software packages. Although we cannot get the *specific* time-of-day contact time information that we could for a real-world satellite, it is reasonably straightforward to calculate similar *average* information from the long-term average contact time plots.

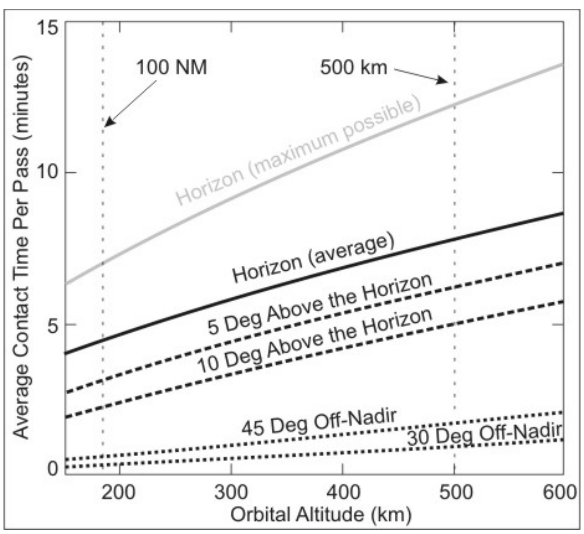

Figure 12. Average pass durations per satellite pass. Fields of regard for three different mission types are shown: SIGINT (horizon), comm/BFT (5 and 10 degrees above the horizon), and imagery (45 and 30 degrees off-nadir). The grey, upper line labeled horizon shows the *maximum* possible contact time for comparison with the average horizon contact line below. All other maximum lines would similarly be about 1.5 times higher than the average lines shown.

A contact occurs when the FOR of a satellite passes over the target. As the FORs on the earth's surface are circles centered on the satellite's nadir point, different contacts will not have the same durations. Their durations depend on the distance of the closest approach of the satellite's nadir point to the target. Figure 11 illustrates this concept. If we assume the FOR passes over the target in a straight line,[36] the minimum pass duration would be an almost instantaneous flicker should the target pass at the very edge of the FOR. The pass duration increases to its maximum value when the satellite passes directly over the target, dragging the entire diameter of its FOR across the target.

For the present study of long-term averages, the average duration of a contact will be related to the average chord length of a circle of diameter equal to the FOR.[37] The maximum chord length is the FOR diameter. The average and maximum chord lengths are obviously dependent upon orbital altitude. Using the relationship that distance equals velocity times time, the average and maximum pass durations can then be found by dividing these chord lengths by the ground speed of the satellite, which is also altitude dependent. Figure 12 displays the average pass durations for the range of satellite altitudes used in the long-term average contact time plots shown previously. (This figure and many of the subsequent figures will show a number of different FORs. However, for the present topic of orbital constraints, only the best-case horizon FOR will be discussed. These figures will be revisited later when we begin to discuss sensor limitations and their relationship to FORs.)As an example, for the orbital altitude of 500 km the average and maximum contact times per pass are 7 min 47 sec and 12 min 13 sec for a horizon FOR, respectively. The maximum contact time will almost never be attained, but it is presented here to demonstrate the absolute best-case scenario. Likewise, it is equally unlikely to have the target pass through the minimum chord.

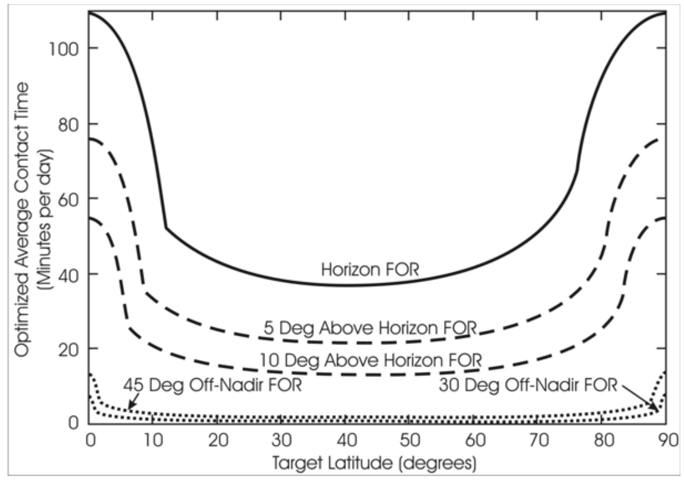

Figure 13. Comparison of satellite coverage for different fields of regard (FOR) from an orbital altitude of <u>100NM</u>. The solid line represents a SIGINT mission, the dashed lines represent comm/BFT missions, and the dotted lines represent imagery missions.

In contrast to Figure 12, which shows *individual* pass durations, Figure 13 shows the optimized contact time *per day*. It is essentially a plot of the heavy line passing approximately diagonally through Figure 9. By dividing the optimized average daily contact time from this figure by the average pass durations from Figure 12, we can determine the average number of contacts (satellite passes) per day.[38] By inverting the number of contacts per day we can also determine the days per contact, or the average revisit time between passes. The gap time, the time when a satellite is not overhead, is just the revisit time minus the pass duration. We can also figure the cost per hour overhead by dividing the acquisition cost of $20 million by the amount of time the satellite would be overhead during the upper limit of its advertised lifetime, one year. Again, the cost estimates will be the most favorable possible to the tactical satellite program, as they use the upper end of the six month to one year advertised lifetime and only include booster/satellite acquisition and not infrastructure or operations costs.

Figures 14 and 15 show these results for satellite altitudes of 100 NM and 500 km, respectively. Note that at the 100 NM tactical satellite altitude reference with a horizon FOR you could expect a single satellite to pass over Baghdad (33 degrees latitude) about 8 times per day and be in view for 4 ½ minutes on average (from Figure 12), resulting in an average gap in coverage of almost 3 hours. The cost of this availability (contact time) is about $88,000 per hour. Placing the satellite higher in a 500 km orbit improves performance a bit. From that vantage the satellite will make ten 8-minute passes per day with an average gap between passes of about 2 ½ hours. The cost for availability at this higher altitude drops to $43,000 per hour.

It is also important to note that commanders have *no* control over exactly when the passes for any satellite would occur. To them, the pass times appear to be pseudorandomly distributed.[39] There would be a number of times where the coverage gaps were much smaller and times where the gaps would be much larger.

Sensor Constraints on Optimized Orbits

The figures calculated above represent the absolute best-case average daily contact times, average pass durations, and average revisit rates that can be obtained, limited only by orbital constraints on the satellite as a whole. To this point in our discussion operational constraints on the satellite payload have not been applied. It is now time to apply those constraints as well.

We have been discussing optimized orbits for horizon FORs. For a few SIGINT missions, these FORs are valid. For other SIGINT missions as well as for the comm, BFT, and imagery missions, they are not. The reason the horizon FOR is not generally valid is due to sensor requirements. For SIGINT, comm, and BFT missions, the emitter of the signal being detected must have an unobstructed LOS to the sensor on the satellite.

Electromagnetic radiation is the basis of virtually all the signals sensed remotely, whether at optical, radio, or other frequencies. Radio waves behave almost identically to light waves, the only differences being due to the different wavelengths of the two forms of electromagnetic radiation. Think of someone shining a laser pointer across a room. If an obstacle gets in the way, the light is blocked. Similarly, if a mountain gets between your car and the broadcast tower of your favorite radio station, the station fades out. Its signal is blocked, too, when LOS is broken.[40]

SIGINT sensors are generally opportunists; they will take in and analyze any signal they can detect. Thus, there is generally no requirement for them to be a certain angle above the

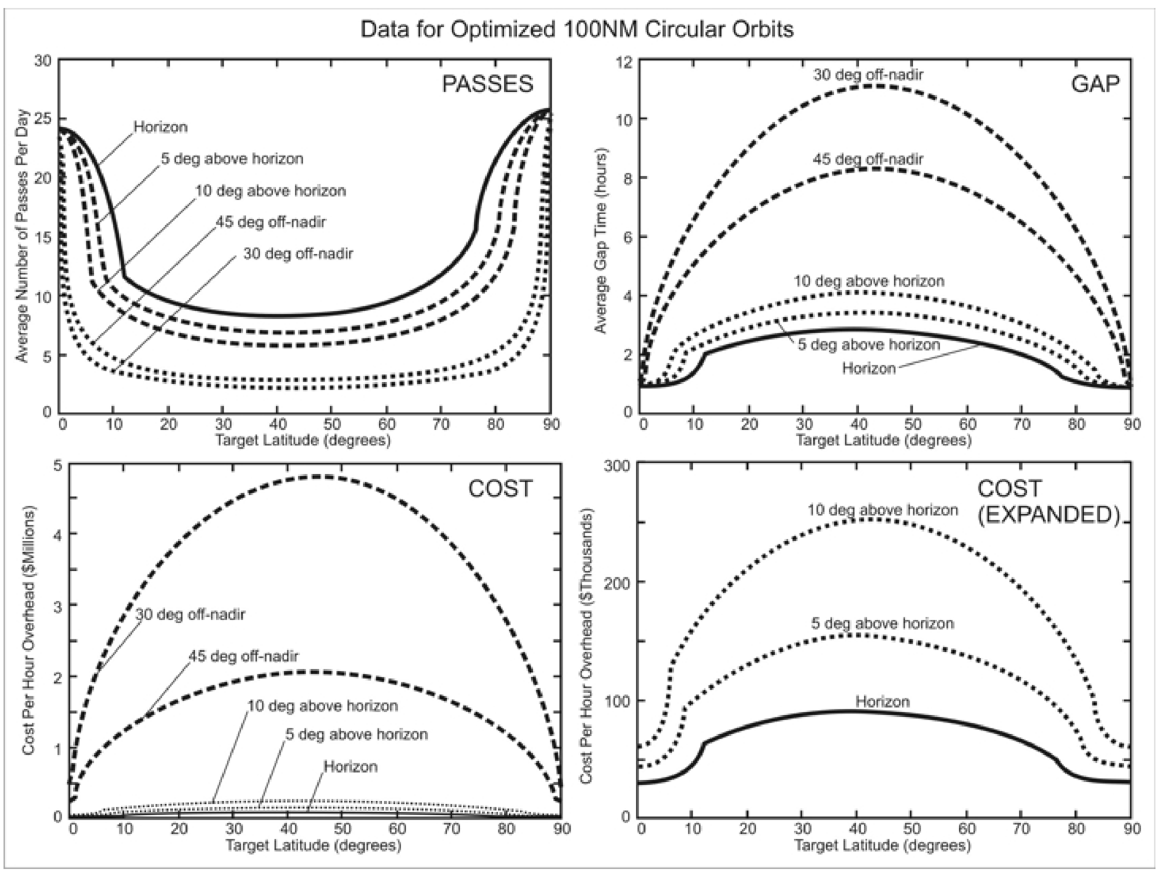

Figure 14. Number of passes, average gap time, and cost data for a tactical satellite in a 100NM orbit. The curves represent data for three mission types: SIGINT (solid), comm/BFT (dashed), and imagery (dotted). Cost data are shown in two panes as the scales between imagery and the other missions are quite disparate.

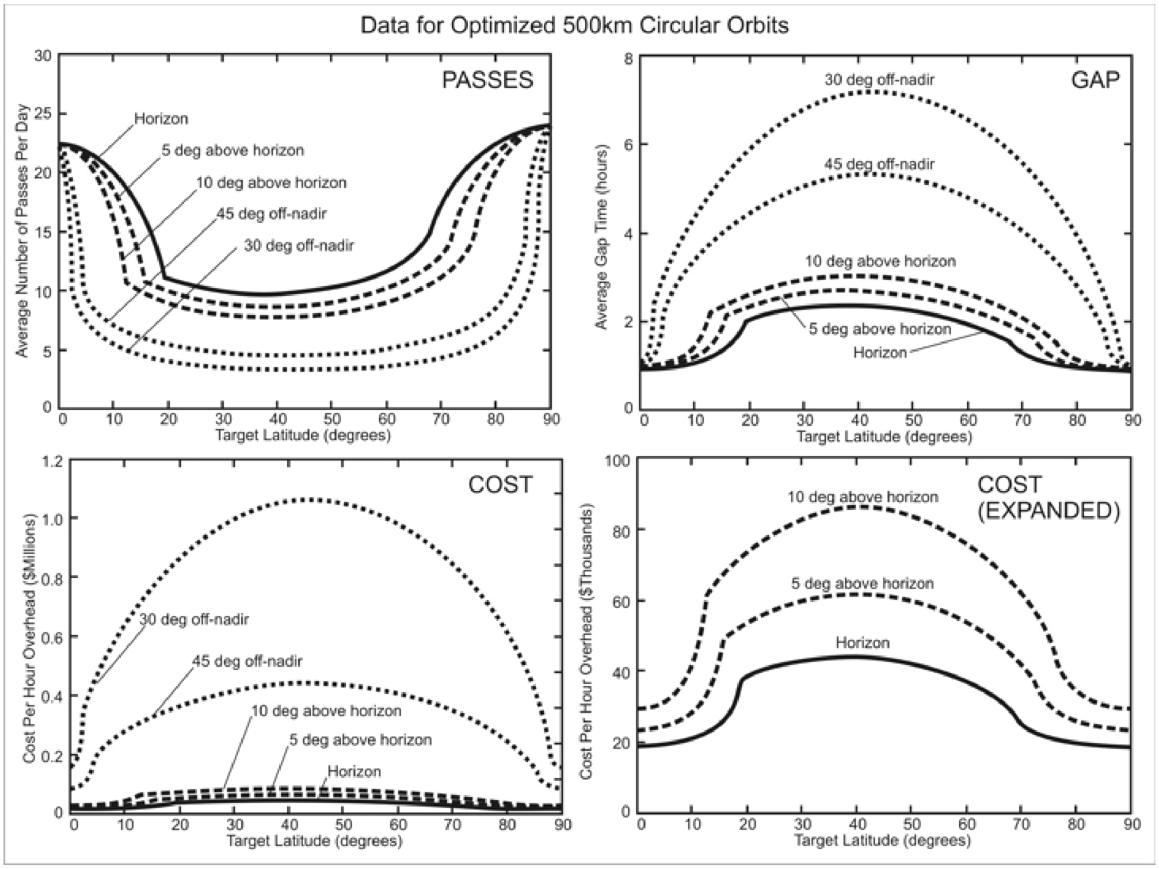

Figure 15. Number of passes, average gap time, and cost data for a tactical satellite in a 500km orbit. The curves represent data for three mission types: SIGINT (solid), comm/BFT (dashed), and imagery (dotted). Cost data are shown in two panes as the scales between imagery and the other missions are quite disparate.

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, it is assumed the horizon FOR is valid for most SIGINT missions.

Comm, BFT, and imagery missions are different. They cannot use the horizon FOR. Comm and BFT missions cannot afford to be opportunistic—the 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 ten 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. Restricting the FOR to five degrees above the horizon has a significant effect on the performance delivered by an optimized orbit. Compare Figures 16 and 17, which show the comm/BFT performance over Baghdad, with the horizon FOR performance previously shown in Figure 6 (p. 12). Not only has the “no coverage” region increased in size, the available daily contact time has also dropped across the board. For example, the maximum contact time per day at the tactical satellite reference altitude decreases

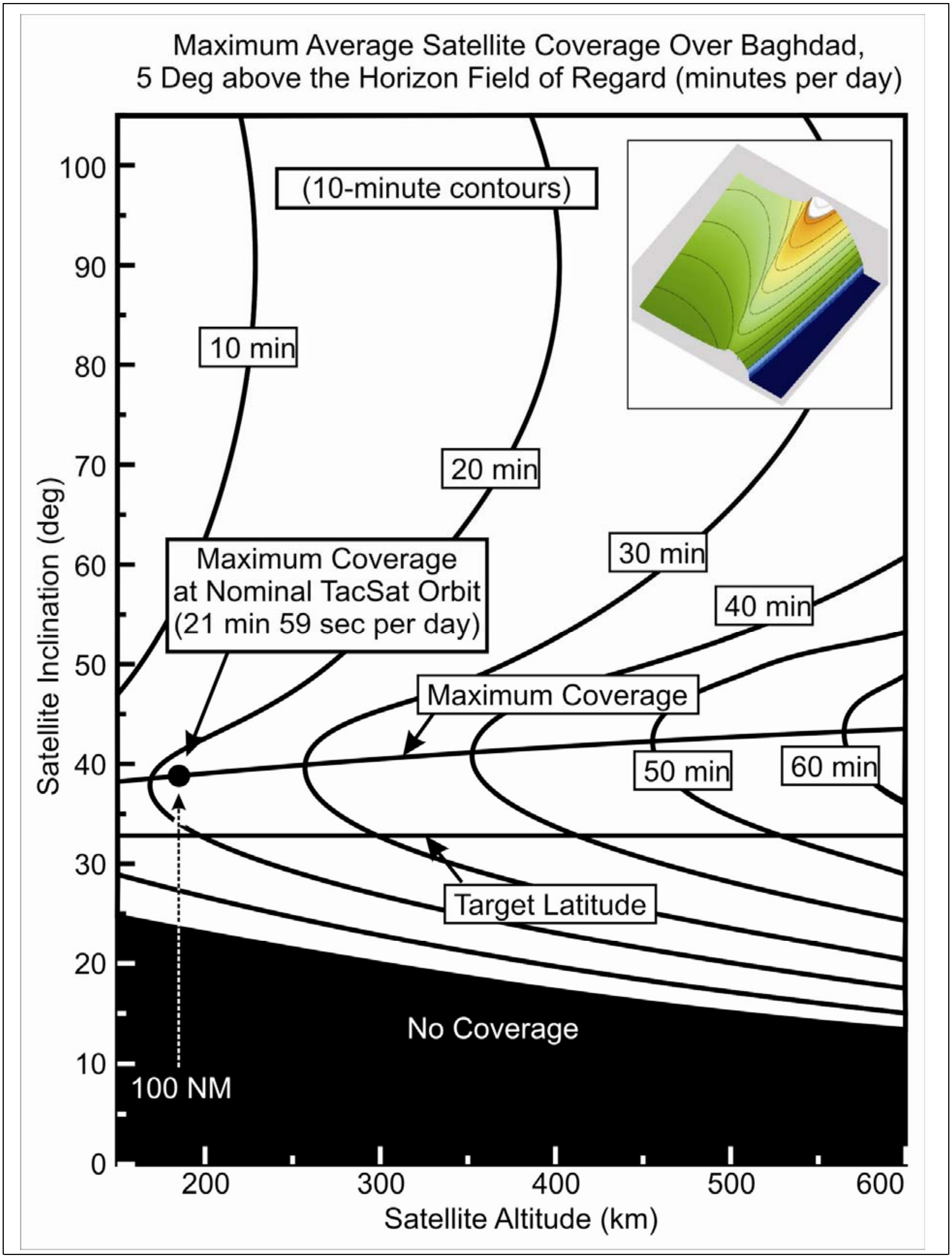

Figure 16. Long-term average contact times over <u>Baghdad</u> with a <u>5 degree above the horizon</u> field of regard.

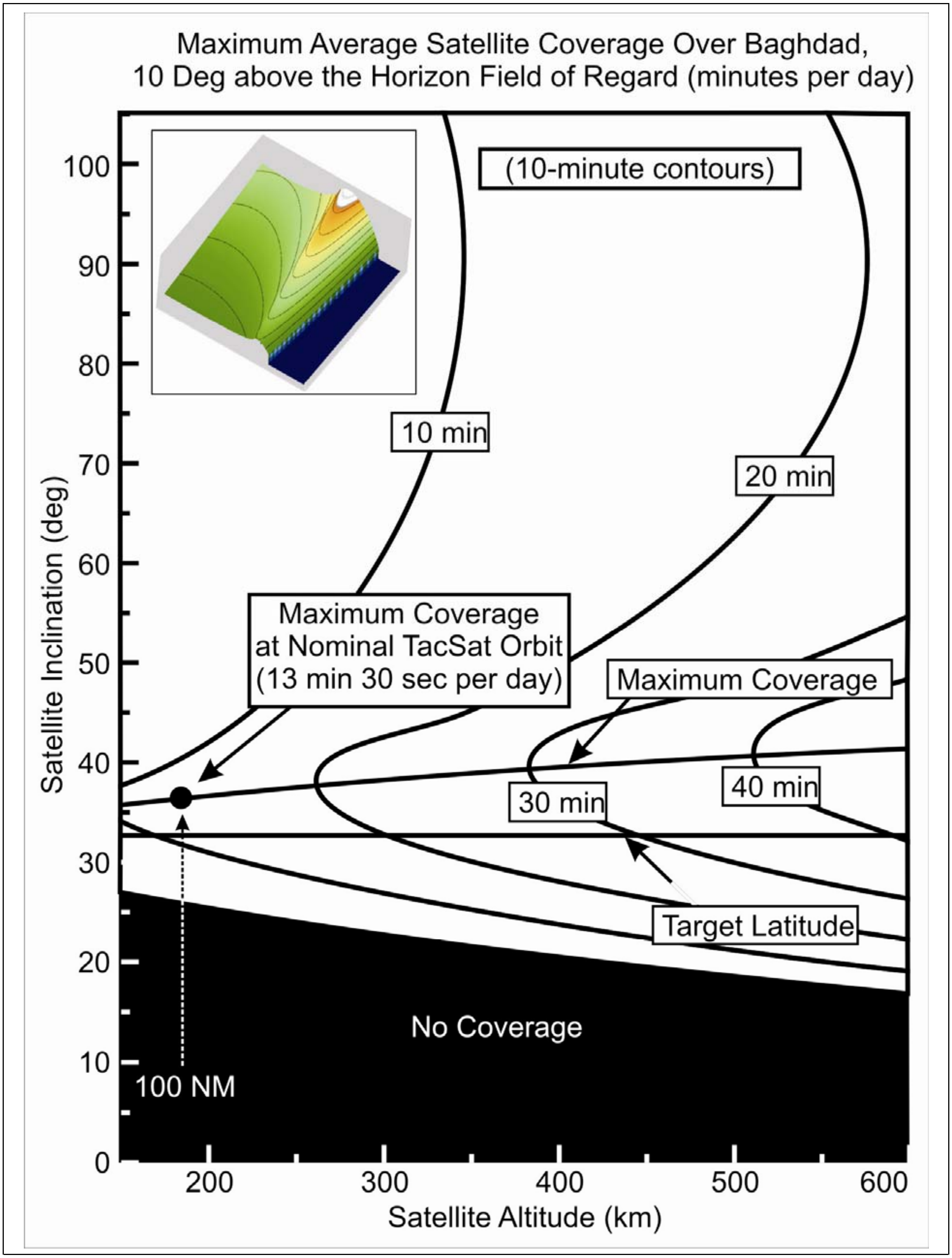

Figure 17. Long-term average contact times over <u>Baghdad</u> with a <u>10 degree above the horizon</u> field of regard.

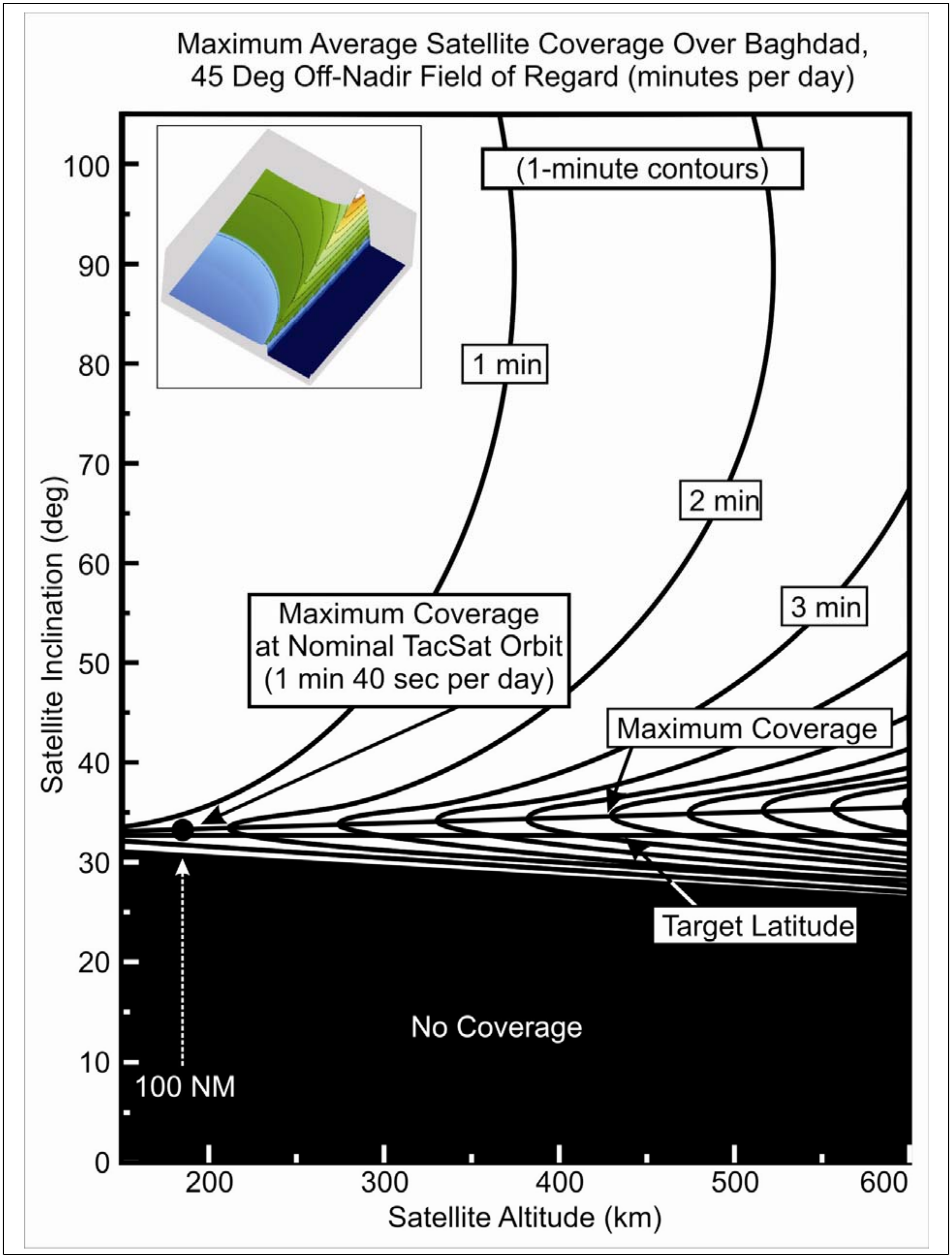

Figure 18. Long-term average contact times over Baghdad with a 45 degree off-nadir field of regard.

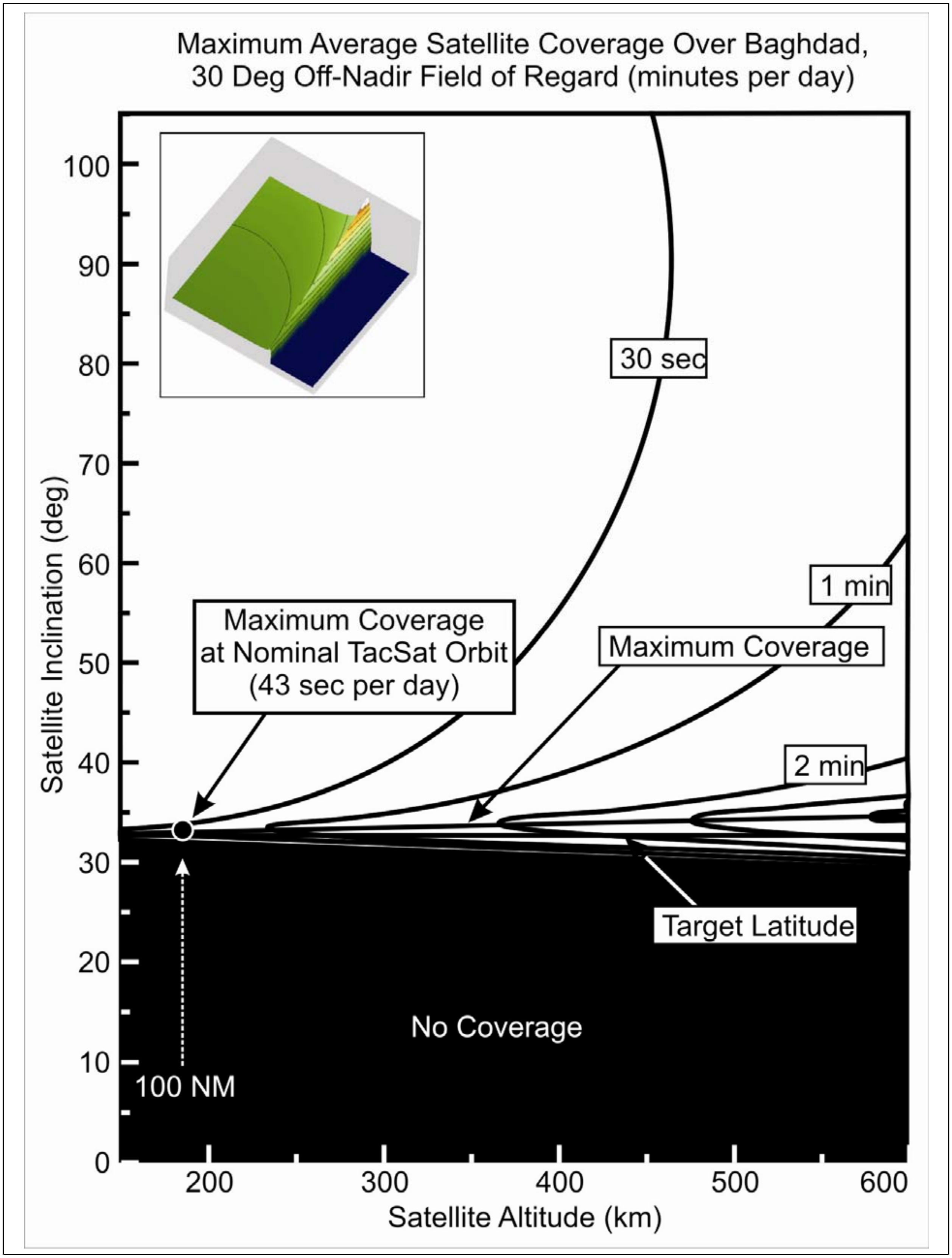

Figure 19. Long-term average contact times over <u>Baghdad</u> with a <u>30 degree off-nadir</u> field of regard.

by 41 percent from 37 to 22 minutes per day. The physical reason for this drop in performance can be seen in Figure 3 (p. 6).

Imagery sensors are even more tightly constrained. Not only must they have LOS like the other missions but, as discussed previously, 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 exceedingly difficult for these sensors to function at night. Even night-capable infrared sensors have a hard time penetrating significant cloud cover. This analysis will ignore the non-trivial limitations of weather and darkness and will present optimized numbers that reflect an ability for imagery sensors to operate at full capability 24/7, realizing that this assumption will significantly overstate the actual capability.

Now compare Figures 18 and 19 (for imagery FORs) with the similar figures we just revisited for typical SIGINT and comm/BFT FORs. These figures show data for satellites optimized to cover Baghdad at a range of altitudes but with different FORs. Figure 9 (p. 16), Figure 20, and Figure 21 show similar data for a fixed altitude of 100 NM across the complete range of target latitudes. Notice the significant, across-the-board decrease in coverage time as the FOR is narrowed from horizon to comm/BFT to imagery FORs. Also notice the significant narrowing of the peaks as the FOR is narrowed.

Although the discussion in previous sections of this paper dealing with orbit optimization was intentionally limited to the best-case (horizon) FOR for pedagogical purposes, many of the previous figures have also included data for four other FORs: five and ten degrees above the horizon for comm/BFT missions and 30 and 45 degrees off-nadir for imagery missions. Now that we have seen why these FORs are an important, additional constraint on satellite performance, we will revisit these figures to investigate their impacts.

In keeping with the goal of giving the tactical satellite program its best chance for success when looking at operational utility, tactical satellite sensors will be assumed to have the capability to perform perfectly with the more favorable of the two FOR cases for each mission, only requiring comm/BFT satellites to be five degrees above the horizon instead of ten degrees, and allowing imagery birds to achieve full functionality all the way out to 45 degrees off-nadir instead of the commercial norm of about 30 degrees. Along with the assumptions of perfectly executed programmatics, the ability to achieve perfect technical solutions, all-weather, day/night operational capability, and the ability to place satellites into the optimal orbits for their missions, these favorable assumptions on achievable FORs will bias the results heavily in favor of tactical satellites when we later look at operational utility.

Again, this study will only consider the relatively mild FOR limitations on mission accomplishment. FOV limitations are typically much more restrictive. To illustrate this concept, the FOR for earthbound photographers with a camera would be analogous to everything they can possibly see from their location (zero to 360 degrees in azimuth and zero to 90 degrees in elevation). Their FOV would be the substantially reduced portion of the world that can be seen through their camera. As the FOV limitations are governed by the choice of the person who commands the payload and not by physics, they will not be considered here. In reality, they will severely limit what can actually be accomplished from orbit. Ignoring FOV limitations are one additional way in which this study is biased in favor of tactical satellites.

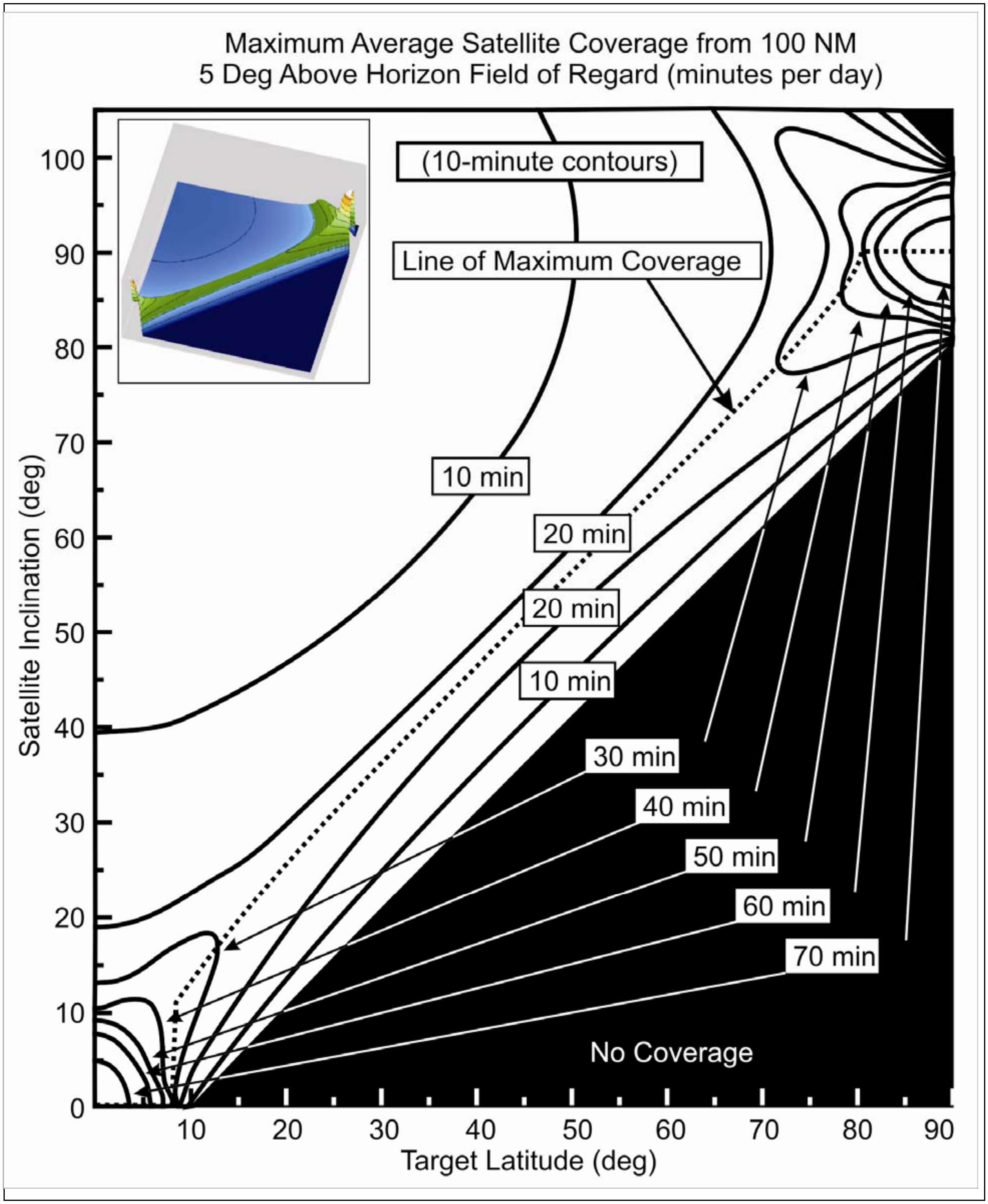

Figure 20. **<u>5 degrees above the horizon</u> field of regard satellite coverage from <u>100NM</u> (185km).**

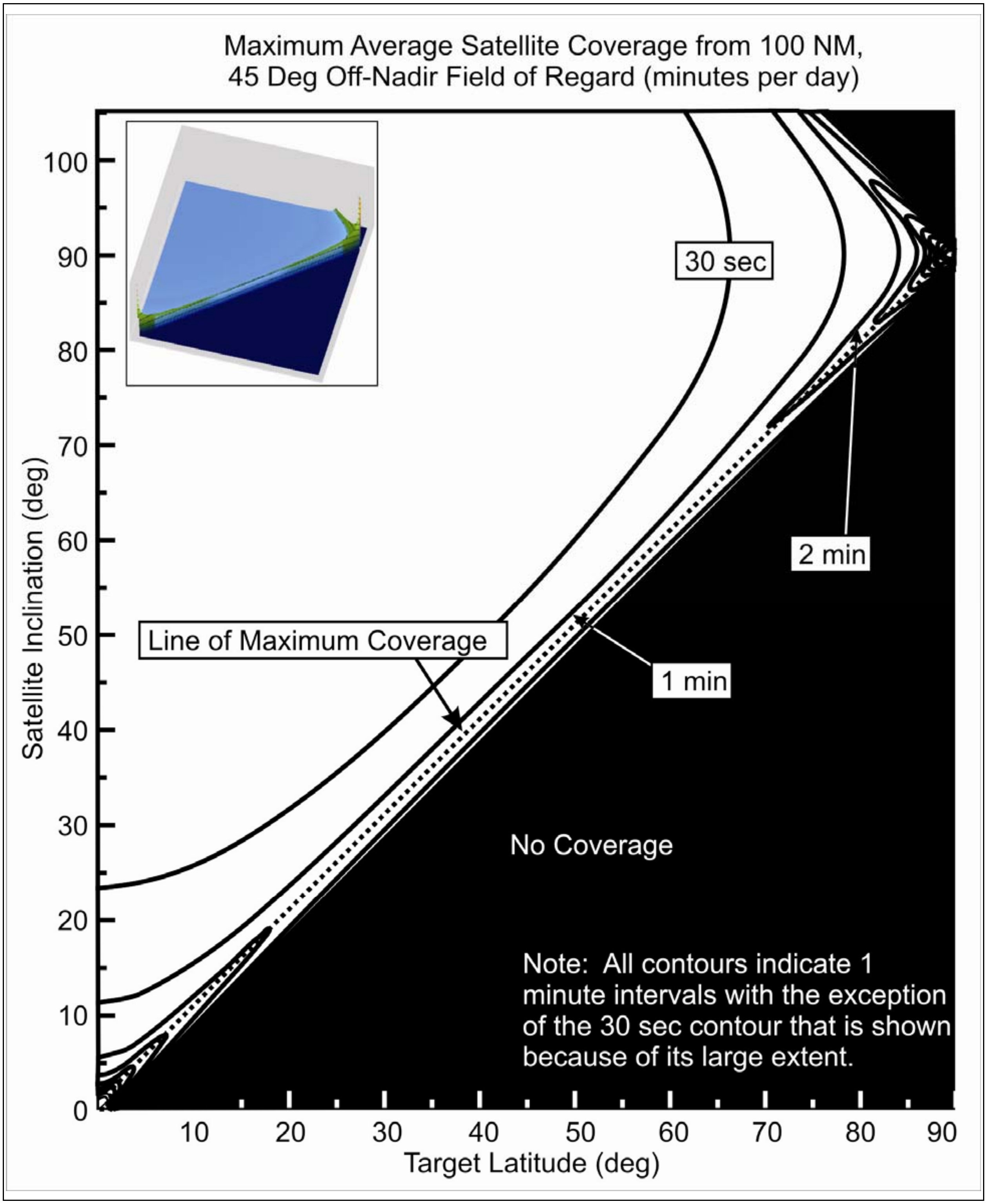

Figure 21. <u>45 degrees off-nadir</u> field of regard satellite coverage from <u>100NM</u> (185km).

Figure 13 (p. 19) showed the optimized average daily contact times for all target latitudes and five FORs: two that are appropriate for imagery missions, two for comm/BFT missions, and one for an idealized SIGINT mission. In the figure the near-symmetry about 45 degrees latitude discussed earlier is readily apparent, as is the marked increase in coverage that polar and equatorial targets receive.[41] One point of the figure is to demonstrate the disparity between contact times over the same targets due to changes in FOR. While the horizon FOR discussed up until this point provides about 45 minutes coverage per day across most mid-latitude targets, switching to a reasonable comm/BFT FOR of five degrees above the horizon drops coverage to about 25 minutes per day for the same targets. The impact is even more severe when you consider imagery missions. Using the generous 45 degree off-nadir imagery FOR, the average coverage time drops to under two minutes per day.

While restricting the useable time overhead is the primary effect of narrowing the FOR, it also has other less noticeable effects. Figure 22 is a plot of the normalized contact times for satellites with five different FORs in 100 NM circular orbits optimized to cover Baghdad. Essentially, it is a plot of the coverage times along a vertical line at the latitude of Baghdad, 33 degrees, in Figure 9 (p. 16), Figure 20, and Figure 21. Since the maximum contact times are of such different scales between SIGINT and imagery missions, it is more useful for the present purpose to show each plot of contact time versus satellite inclination in terms of fractions of the maximum amount. From the figure, it is clear that the narrower the FOR, the more closely the optimal satellite inclination matches the target latitude, as evidenced by the steady march of the locations of the peaks toward the target latitude as the FOR is narrowed.

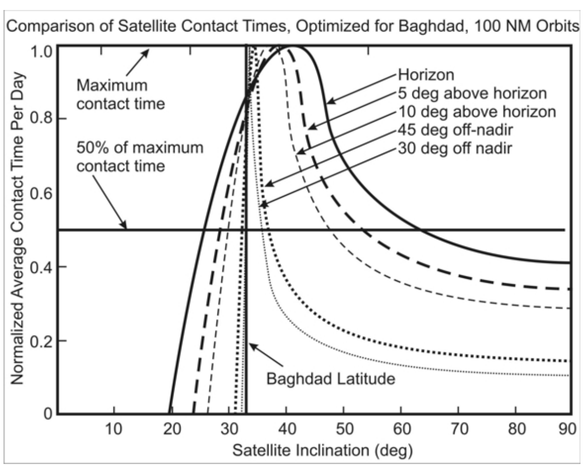

Figure 22. Comparison of the width and location of the peaks of the average daily contact times for several fields of regard.

While the convergence of latitude and optimal inclination is a somewhat esoteric fact, a much more operationally applicable trend can also be discerned from this figure. As the FOR decreases, the width of the coverage time curve decreases markedly. Using the rather arbitrary measure of width of where the coverage time drops to half its maximum value, this trend in curve width is quite apparent. The narrowness of the average contact time curves will be discussed at more length later when we consider flexibility of retargeting in the operational utility analysis section of this paper. **Error! Reference source not found.** summarizes the peak locations and curve widths from Figure 22 for the five FORs discussed in this study. To make this apples-to-apples FOR comparison more clear, the ground-based FORs that include reference to the horizon have been converted into satellite-based off-nadir angles in the first data row of the table. For example, for a satellite in a 100 NM orbit, the ground-based reference of five degrees above the horizon equates to a satellite-based reference of 75.5 degrees off-nadir. Those numbers represent the same physical situation, just from different points of view. (Figures 3 and 4 (pp. 6-7) show the physical relationship between satellite-based and ground-based angles.) In the table, note the approach of the inclination of maximum contact time toward the latitude of Baghdad (33 degrees latitude) as the FOR is narrowed. Also note that the contact time becomes a very sensitive function of inclination for

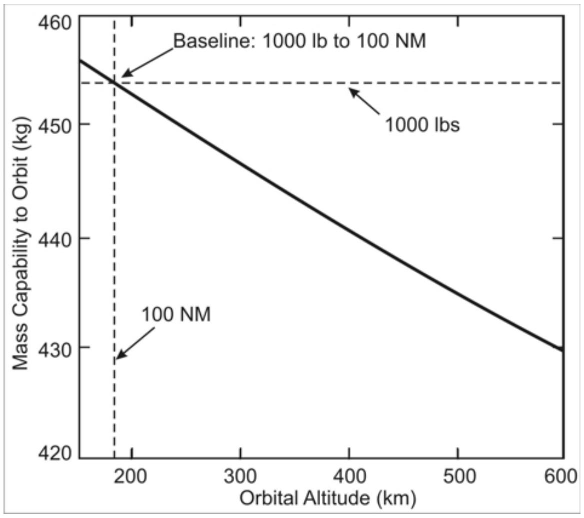

Figure 23. Mass that can be boosted to a range of orbits using the same amount of energy, based on a booster capable of placing a 1000-pound payload in a 100NM orbit.[42] Results based on a highly simplified model; actual mass capability would be substantially less at altitudes higher than the reference orbit.

narrower FORs. Again, the sensitivity of this function will be discussed later in relation to the opportunistic use of tactical satellites for other than their designated targets.

Returning to Figure 13 (p. 19), the effect of narrowing the FOR on the amount of time per day a satellite is overhead is striking. Constraining the FOR to the comm/BFT missions essentially halves the daily amount of time overhead, while the imagery constraint shrinks the daily contact time to a few percent of its horizon value. The pass duration (Figure 12, p. 18) also shrinks markedly. The combination of these two changes has dramatic effects on the number of passes per day, average gap time, and cost per hour overhead, as demonstrated in Figure 14 (p. 20) and Figure 15 (p. 21). Tables 1 and 2 (p. 3) highlight many of these differences for the Baghdad case.

General Term for FOR	Horizon (satellite-based)	5 Degrees Above Horizon (ground-based)	10 Degrees Above Horizon (ground-based)	45 Degrees Off-Nadir (satellite-based)	30 Degrees Off-Nadir (satellite-based)
Satellite-Based FOR (Degrees Off-Nadir)	76.4	75.5	73.1	45	30
Inclination of Maximum Contact Time (Degrees)	41	38.5	37	34	33.5
Width of Contact Time Curve (Degrees of Inclination)	37.5	25	18	4.5	2.5

Table 3. Comparison of curve parameters from Figure 22 for a satellite at 100 NM optimized for coverage of Baghdad. Inclinations and widths are given to the nearest half-degree.

Section 3

Increasing Altitude to Increase Coverage

Although the tactical satellite reference orbit is 100 NM, it should be clear from a number of the preceding figures that raising the altitude could pay significant dividends with respect to contact time. By moving higher, the FORs grow larger and the satellite speeds slow down, both of which will increase contact time. Additionally, at higher altitudes the already tenuous atmosphere becomes even thinner, allowing satellites to stay aloft for much longer periods.

There is a price to be paid, however, for increasing orbital altitude. It takes more energy to get to the higher orbit, and this energy does not come for free. It is possible to buy larger boosters to put satellites into higher orbits, but such boosters do not currently meet the tactical satellite goals for cost and responsiveness. Use of the same booster to go to a higher altitude is assumed for this paper. The energy that can be supplied by this booster, then, cannot change. The energy of a satellite in orbit is related to its velocity, altitude, and mass. In any specified orbit, altitude and velocity are not independent, so they cannot be controlled separately. Thus, if we want to increase the altitude of a satellite while keeping constant the energy required to place it in orbit, we must decrease its mass. As can be seen from Figure 23, the mass that can be put into higher orbits decreases almost linearly as altitude increases. The mass decrease, however, is rather unsubstantial. Using the same booster and an optimistic, highly simplified energy model, it takes the same amount of energy to put 1000 lbs. (454 kg) into a 100 NM (185 km) orbit as it does to put a 958 lb. (435 kg) payload into a 500 km orbit.[43]

Although attained at about a 5 percent mass penalty, the higher orbit also has the benefit of allowing the satellite to have a much longer lifetime. Based on standard atmospheric models and assuming no thrust is applied to counteract drag, a small satellite in a 400 km orbit will last several hundred times longer than a similar satellite in a 200 km orbit.[44] Keeping satellites flying longer requires carrying aloft substantial quantities of fuel, fuel that costs a great deal in terms of the satellite's mass budget. Increasing the orbital altitude above the tactical satellite reference altitude is an easy way to get a rather substantial increase in lifetime without having to expend as much precious fuel. However, much of this extra lifetime is somewhat irrelevant as it greatly exceeds the tactical satellite goal lifetime of six months to one year. Extending the lifetime would certainly reduce the per-hour costs of the satellite, all else being equal. However, the goal lifetime was determined as the maximum amount of time that cheap, not-space-qualified parts would be likely to last before failure—and these inexpensive parts are critical to being able to meet the $20 million acquisition-through-launch budget goal.[45]

Employing Constellations to Increase Coverage

One of the major unfilled requirements of the ongoing conflicts in Iraq and Afghanistan is the need for persistent C2ISR. The persistence commanders almost unfailingly call for is 24/7, stay-and-stare persistence. [46] As shown, it is not possible for a single satellite in LEO to provide this persistent coverage. COCOMs are well aware of this limitation.[47]

Frequently, proponents of tactical satellites propose fielding constellations of multiple satellites in order to mitigate the size of the gaps in coverage. According to Major Adam Mortensen, Branch Chief for Space Demonstrations at the Air Force SMC's Transformation and Development Directorate (TD),[48] "you can get 24/7 coverage, depending on how many [satellites] you put into . . . different [orbital] planes."[49] While a true statement, in many cases the answer to the question "how many" may not be palatable to those with a constrained budget. A recent Scitor study for STRATCOM determined that it would take about 80 satellites in 500 km orbits to provide 24/7 coverage of the globe.[50] While extremely comprehensive in nature, this study exclusively used horizon FORs for its calculations and optimized its results to provide 24/7 global coverage, conditions specified by Scitor's customer. As discussed above, FORs are mission-driven and the horizon FOR specified for the Scitor study is not always the appropriate one. Restricting the FOV to less than the horizon will significantly increase the number of satellites required to provide similar seamless coverage. Since this is an effort to determine the *tactical* utility of LEO satellites, the requirement for continual *global* coverage provided to STRATCOM seems quite excessive for this purpose. Let us now consider where the desire for tactical effects will drive the total constellation number.

Instead of providing the obviously strategic mission of global 24/7 coverage, it is more instructive for this purpose to investigate the constellation requirements for achieving persistent coverage of a tactical region. Since the exact pass times of each satellite in a constellation are

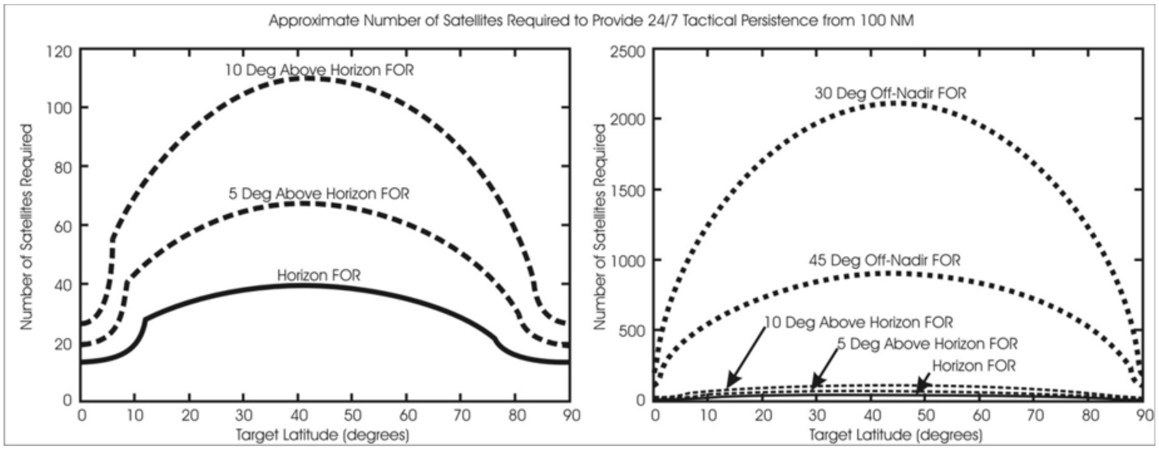

Figure 24. Approximate number of satellites required to populate a persistent constellation orbiting at <u>100NM</u>. The curves represent data for three mission types: SIGINT (solid), comm/BFT (dashed), and imagery (dotted). Two panes are shown due to the disparity of scale between the different fields of regard.

pseudorandomly distributed, it is somewhat difficult to calculate the exact satellite requirements for a persistent constellation. Instead, a simple estimation method will give a reasonably good number on the low end of that actually required. This low-end number continues the attempt to present the tactical satellite program in the best light possible.

A simple approach to approximating the number of satellites required to give 24/7 coverage of a single spot on earth can be found by dividing the minutes in a day by the average number of minutes per day spent overhead by a single satellite. This number would be that required for a long train of satellites to pass sequentially over the target. On average, the target would leave the FOR of one satellite just as it was entering the FOR of the next satellite in the train. While setting up and maintaining the relative positions of such a train of satellites would be quite difficult in practice, the method does give a low-end ballpark number for the required number of satellites. It is important to remember that these estimates are based on average coverage; there will be many days where even these constellations would fall short of the goal of 24/7 coverage of the target.

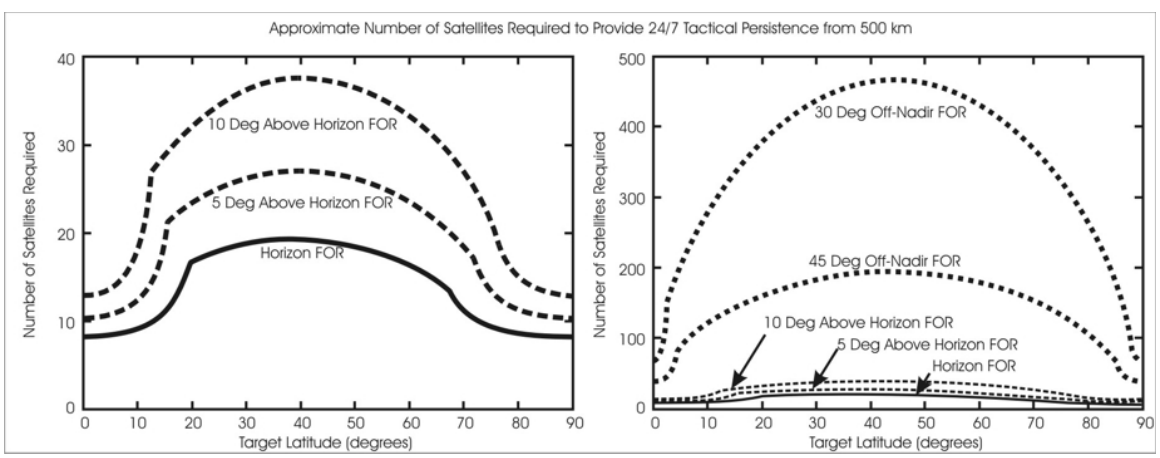

Figure 25. Approximate number of satellites required to populate a persistent constellation orbiting at <u>500km</u>. The curves represent data for three mission types: SIGINT (solid), comm/BFT (dashed), and imagery (dotted). Two panes are shown due to the disparity of scale between the different fields of regard.

Figures 24 and 25 show the requirements for the number of satellites orbiting at 100 NM and 500 km to provide constant tactical coverage. As can be seen, for a horizon FOR it would take at least 39 satellites to provide persistent coverage over Baghdad. Raising the altitude to 500 km decreases the requirement to 19 satellites. For comm/BFT missions with a five degree look-up requirement, the constellation numbers rise somewhat to 66 and 27 for 100 NM and 500 km orbits, respectively. For the constrained FOR inherent in imagery, 45 degrees off-nadir, the persistent constellation requirements are at least 188 for a 500 km orbit and 867 for the tactical satellite reference altitude of 100 nm. Every one of these $20 million satellites would also need to be replaced after, at most, one year on orbit, based on the satellite lifetime goals of the program.

Extending the Analysis to Elliptical Orbits

In an attempt to avoid the financial hurdle imposed by the physical constraints on objects orbiting in LEO, tactical satellite proponents also advocate using a highly elliptical orbit based on those used by Russian Molniya comm satellites. Satellites orbiting in the equatorial geostationary orbits normally used by comm satellites are very close to or below the horizon for much of the Russian landmass. To get around this limitation, the Russians put much of their comm capability on satellites in highly elliptical "Molniya" orbits that are designed to spend a large fraction of their orbital periods in view of specific high-latitude locations. The apogees of these orbits are almost 40,000 km above the earth, even further than GEO orbits, while their perigees are generally between 200 and 2,000 km (example shorthand: 200 x 40,000 km).[51] These apogee and perigee distances are chosen for two reasons. First, they cause the satellites' orbital periods to be half a day so their ground tracks repeat. Second, remember that the closer to earth a satellite is, the faster it moves. The Molniya apogee is designed to occur as the satellite reaches its maximum northern latitude. The satellite and its huge FOR move very slowly there, so it spends a great deal of time in this part of its orbit. As it accelerates back toward its perigee, it zips past the earth's southern hemisphere, providing a very small, rapidly moving FOR there. Since the point of the satellite is to give good coverage of Russia, this setup works quite well. Additionally, Molniya orbital inclinations must be set at exactly 63.4 degrees so their apogee point does not shift to the southern hemisphere over time.[52] With such attributes as repeating ground tracks and long hang times over high latitudes, it takes only two or three satellites in a Molniya constellation to provide constant coverage of Russia.[53]

It takes a huge amount of energy to get any appreciable mass into a Molniya orbit, energy well in excess of what any envisioned responsive booster could affordably provide. To provide similar benefits from an orbit that actually might be reached by a responsive booster, the "Magic Orbit" (occasionally called the MAJIC orbit[54]) is being offered as an alternative to circular low-earth orbits by proponents such as SMC/TD (Directorate of Development and Transformation) and AFRL.[55] These magic orbits are essentially lower-altitude versions of the Molniya. Their perigee/apogee distances are greatly reduced (approximately 500 x 8,000 km), and the period is only 1/8 of a day

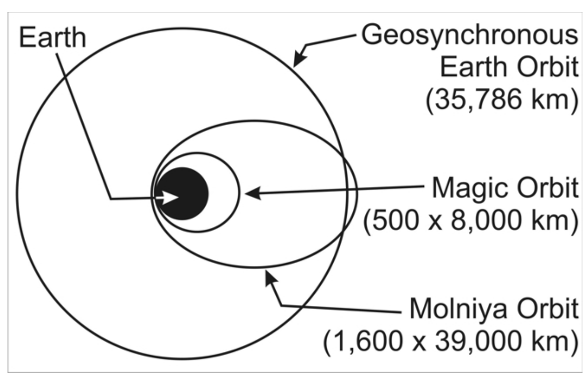

Figure 26. Scale drawing of magic, Molniya, and GEO orbits. Numbers shown are altitudes. The tactical satellite circular orbit is not visible at this scale.

instead of half. The FOR sizes are substantially smaller at apogee. Figure 26 shows the relative sizes of the GEO, Molniya, and magic orbits. Figure 27 shows representative apogee and perigee FORs for a magic orbit along with the ground track that repeats every eight orbits.

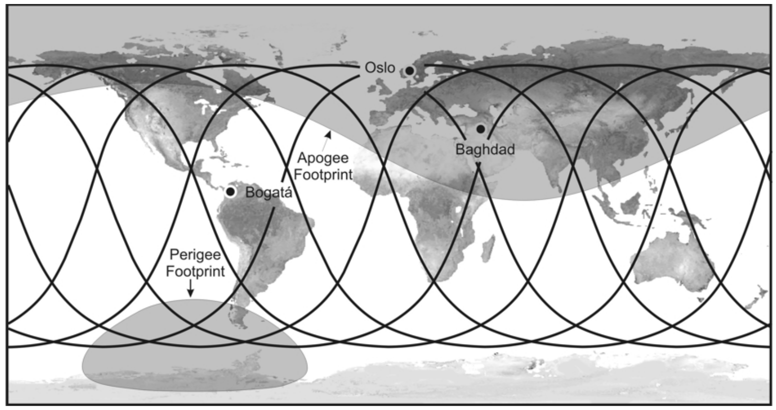

Figure 27. Magic orbit apogee and perigee fields of regard and the eight repeating ground tracks for an arbitrary longitude of the ascending node. Note the difference in field of regard size between apogee and perigee.

The advantage of a magic orbit is that it greatly reduces the number of satellites required to provide 24/7 coverage of a tactical area. Instead of the minutes per day of coverage provided by LEO satellites, magic satellites provide hours. To provide such coverage over Iraq, for example, it would only take six satellites in magic orbits using a horizon FOR.[56] Six is obviously a much better number than the twenty to hundreds required from circular LEO satellites.

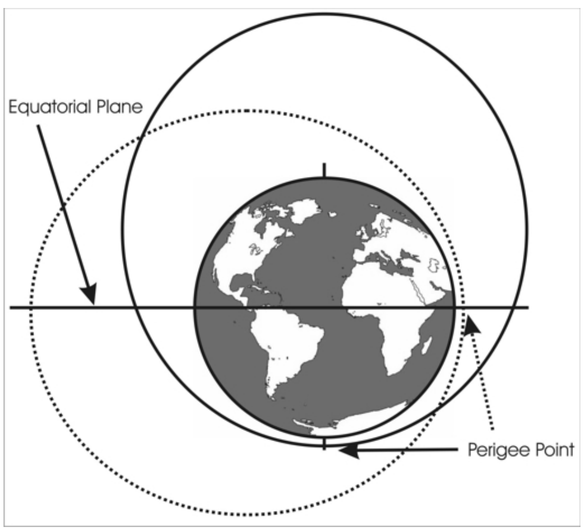

Figure 28. Example of the argument of the perigee. For these polar orbits with the satellite assumed to be traveling counterclockwise from this perspective, the argument of the perigee is 0 degrees for the dotted orbit and 270 degrees for the solid orbit.

Again, for the purposes of this study, the magic orbit will be optimized to provide the best coverage of a specific, tactically-sized area much as was done with the circular orbits discussed earlier. In this case, the orbital inclination is not a free parameter, as it must be set to the 63.4-degree value that prevents the location of the perigee from moving. The location of the perigee, however, is a free parameter. This location can be described by an angle called the argument of the perigee, a measure of the angular distance between the point where the satellite crosses the equatorial plane in a northerly direction and the point where the closest approach to the earth occurs, measured in the direction of the satellite's motion. Figure 28 demonstrates this concept for a polar (90 degree inclination) orbit. In that figure, a satellite in the solid orbit would spend most of its time above polar regions where its high altitude would cause its speed to be very slow. A satellite in the dotted orbit would spend an average amount of time over equatorial regions since its apogee and perigee are both equatorial, but would obviously spend less time in the northern hemisphere than a satellite in the solid orbit.

Figure 29 shows the effect of changing the argument of the perigee on the contact time over the example cities.[57] As can be seen, the orbits that maximize the contact time have arguments of the perigee of approximately 270 degrees. In other words, coverage time is maximized when the orbit's apogee occurs just as the satellite reaches its maximum northerly limit. This result is general for almost the entire northern hemisphere, breaking down slightly for very low latitude targets.[58]

Now that the optimal argument of the perigee has been determined, consider the numbers related to optimized magic orbits. Figure 30 shows the average daily contact time as a function of target latitude for satellites in magic orbits. Three curves are shown for the two potential missions a satellite in such an orbit could perform: SIGINT and comm/BFT. The reason the use of magic orbits for imagery missions has been discounted will be discussed below. As can be seen, the daily contact times for magic orbits are significantly higher than those for the LEO cases studied earlier, ranging from about three to almost 12 hours per day. It is these long contact times that allow the constellation sizes for magic orbits to be so much smaller than for low earth circular orbits.

There are several operational constraints associated with magic orbits, however. As mentioned above, resolution and signal strength can become problems when range increases.

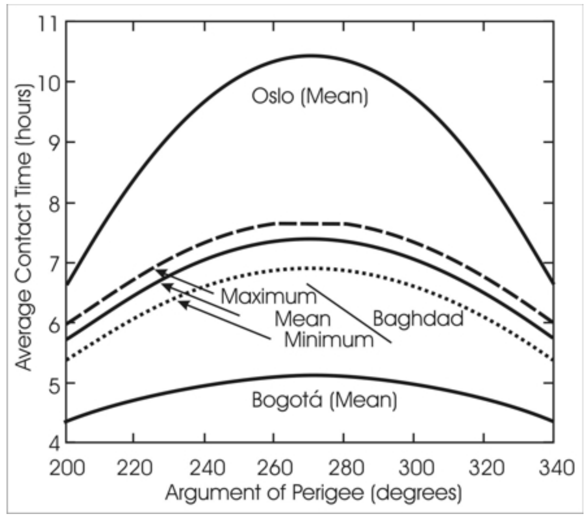

Figure 29. Average daily contact time for magic orbits as a function of argument of the perigee. The curves labeled "Mean" show the contact time at the specified argument of the perigee averaged across all longitudes. The curves labeled "Maximum" and "Minimum" show the contact time at the absolute best- and worst-situated longitudes, respectively.

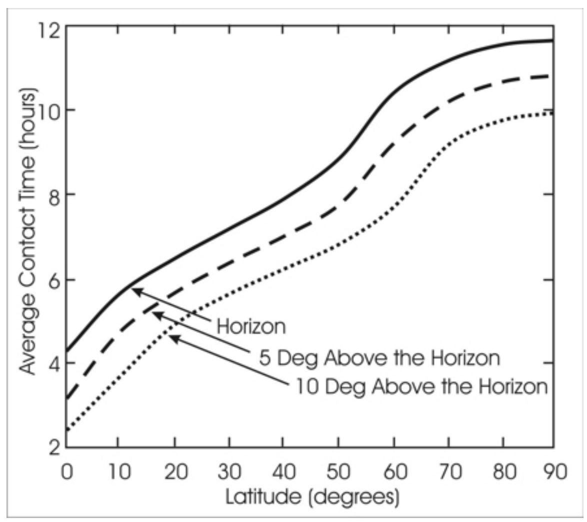

Figure 30. Average daily contact time for magic orbits as a function of latitude for three fields of regard.

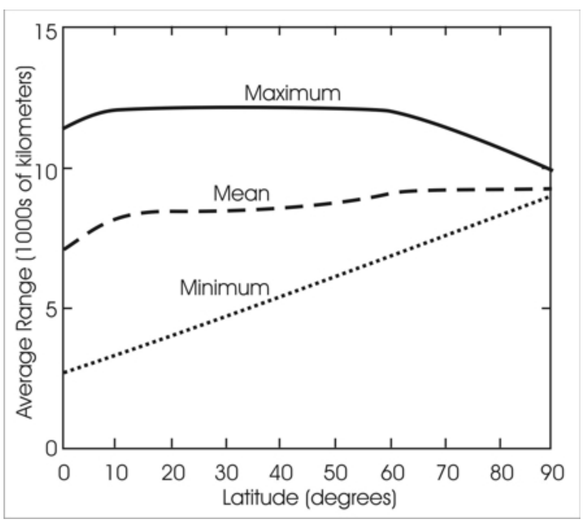

Figure 31. Average range from a satellite in a magic orbit with a field of regard of five degrees above the horizon as a function of latitude. The curve labeled "Mean" shows the range averaged across all longitudes. The curves labeled "Maximum" and "Minimum" show the range at the absolute best- and worst-situated longitudes, respectively.

Figure 31 shows the minimum, average, and maximum ranges from target to satellite when the target is within the 5-degree-above-the-horizon comm/BFT FOR. Satellites in magic orbits are, on average, 17 times further from a target than they are in a 500 km circular orbit. This additional distance is a huge disadvantage for both the linear resolution function relevant to

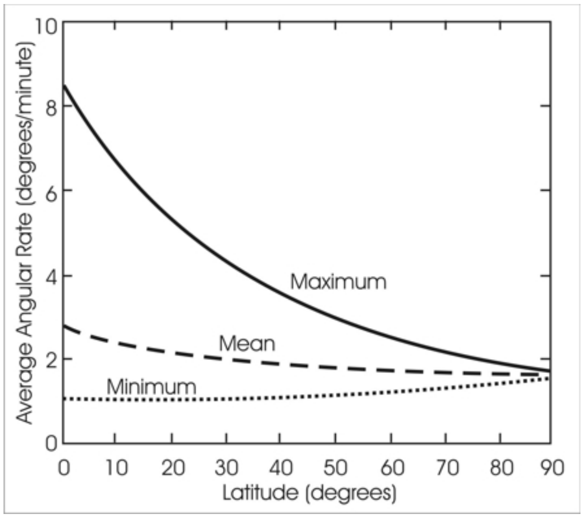

Figure 32. Average apparent rate of motion across the sky for a satellite in a magic orbit with a field of regard of five degrees above the horizon as a function of latitude. The curve labeled "Mean" shows the rate averaged across all longitudes. The curves labeled "Maximum" and "Minimum" show the rate at the absolute best- and worst-situated longitudes, respectively.

imagery applications and the very basic $1/r^2$ signal strength attenuation function relevant to all electromagnetic applications.[59]

Additionally, unlike most comm satellites used today, tactical satellites will not be in geostationary orbit. They will move across the sky, constantly changing not only position but range. Figure 32 shows the minimum, average, and maximum angular rate at which the satellite moves across the sky for various latitudes. Figures 33, 34, and 35 show the apparent paths of a single satellite in a magic orbit across the sky from the three example cities of Bogotá, Baghdad, and Oslo, respectively. As can be seen from the non-uniform spacing between timing dots in the figures, the satellites not only move, but change apparent speed during their passes.

While range and apparent motion both add complexities to the tactical satellite problem, an even larger impediment to putting tactical satellites into magic orbits comes from the environment. The Van Allen radiation belts are two doughnut-shaped shells surrounding the earth containing high energy particles (both protons and electrons in the inner belt—about 1,400

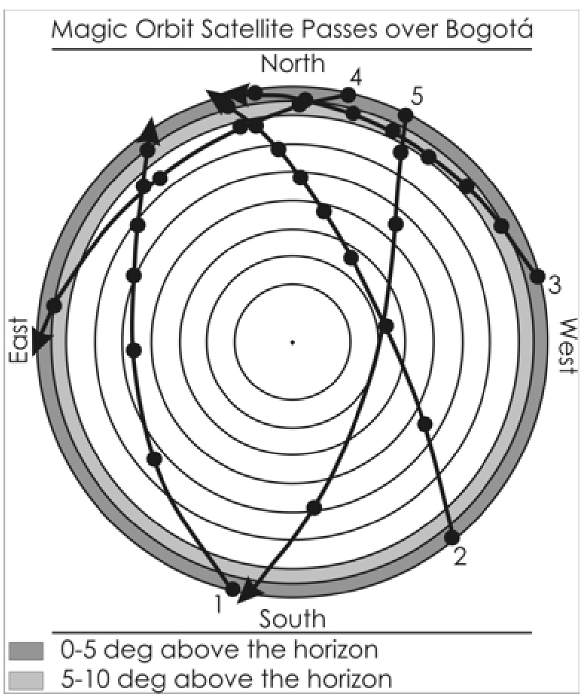

Figure 33. Representative repeating magic orbit passes over Bogotá. Ten-degree elevation rings. Dots are spaced ten minutes apart. Numbers indicate the order of the passes.

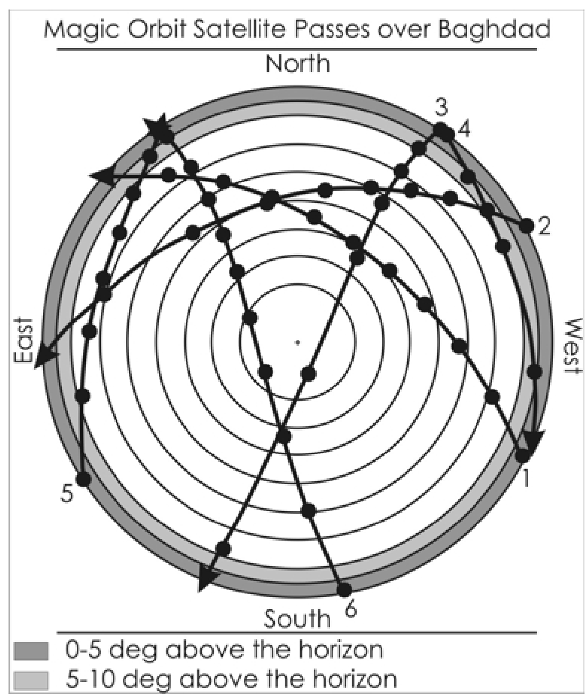

Figure 34. Representative repeating magic orbit passes over Baghdad. Ten-degree elevation rings. Dots are spaced ten minutes apart. Numbers indicate the order of the passes.

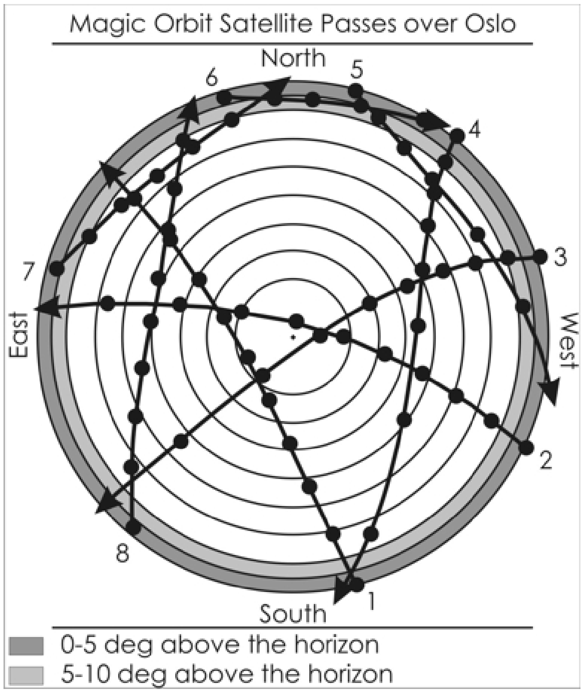

Figure 35. Representative repeating magic orbit passes over Oslo. Ten-degree elevation rings. Dots are spaced ten minutes apart. Numbers indicate the order of the passes.

to 10,000 km in altitude—and primarily electrons in the outer belt—between about 13,000 and 32,000 km altitude).[60] Figure 36 shows the locations of the hearts of the belts in relation to the LEO and magic orbits. It must be noted again that the shells are toroidal and the orbits do not intersect the belts at all times as shown in the simplified schematic. However, the orbits do pass through the hazard region on an extremely regular basis. At times, even LEO satellites can pass through anomalous regions of the Van Allen belts.

Electronics are easily damaged by high energy particles. As the feature sizes on COTS electronics become smaller and smaller, this vulnerability only increases and they become sensitive enough to be damaged even when inside heavy shielding. Using radiation-hardened, space-qualified electronics is the way the space industry commonly overcomes these problems, but such components are frequently several generations behind cutting-edge and are thus much slower and require higher power than current models. The lower demand and higher manufacturing costs drive the price of these radiation-hardened components to very high levels.[61] The stringent requirements placed on components by the mil-spec system add to the cost as well. To keep costs down, the tactical satellite proponents plan to use exactly the kind of COTS circuits that are so vulnerable to radiation-induced failure.[62]

For LEO satellites, using COTS electronics as a cost-control measure seems reasonable, especially when the short lifetime of the satellites is taken into account. In fact, it seems that aside from atmospheric drag, anticipated electronics failure would be the limiting factor for tactical satellite lifetimes. LEO satellites generally experience a relatively light radiation environment, orbiting below the vast majority of the Van Allen belts. GEO satellites are above most of the belts, but are occasionally exposed to direct solar wind radiation, especially during times of high solar activity. Satellites in magic orbits traverse the heart of the inner Van Allen belt about sixteen times a day. Although the maximum amount of radiation experienced by a satellite is a strong function of orbital inclination, the 63 degree magic inclination is still within the extreme danger zone for radiation-induced electronic failure.[63]

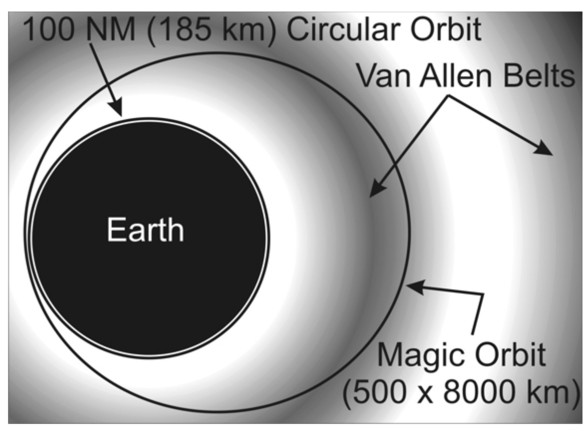

Figure 36. Scale drawing of the tactical satellite reference orbit and magic orbit. Orbits and belts are not necessarily co-planar but are shown in this manner to demonstrate scale.

Finally, there is an energy price to be paid to get satellites into magic orbits. They are much higher than the tactical satellite reference of 100 nm. Not only is the energy required to reach an orbit with such high apogees and perigees much larger than required for the same mass satellite in LEO, an energy-expensive post-launch inclination change will be required to insert the satellite into the required 63 degree plane. The reason for this plane-change requirement is that neither the eastern or western US launch ranges have the capability to launch directly into this inclination.[64] Doing so would require the booster to make a low-altitude pass over land masses, posing an unacceptable risk to populated areas should the booster fail.[65] Figure 37 shows the allowable launch paths and their associated inclinations from the two CONUS ranges. [66] Not counting the required plane-change maneuver, a booster with the capability to just put the 1000 lb. tactical satellite reference mass into the 100 NM reference orbit would only be able to put a 500 lb. payload into a magic orbit.[67]

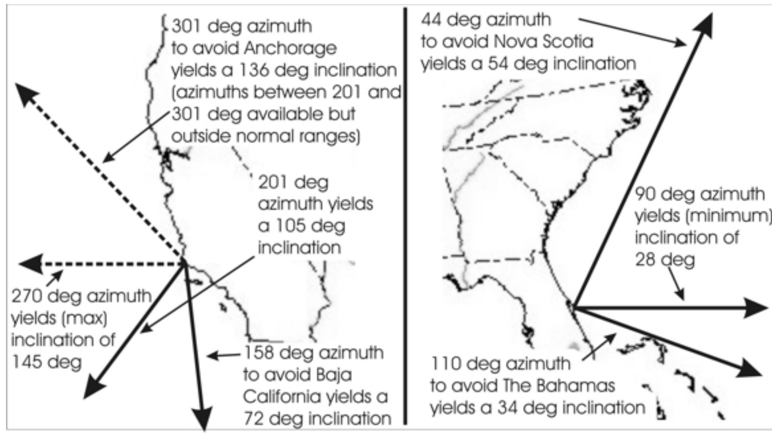

Figure 37. Launch restrictions on available azimuths from Vandenberg AFB (left pane) and Patrick AFB (right pane). Inclinations between 28 and 54 degrees are available from Patrick. Inclinations between 72 and 145 degrees are available from Vandenberg.

Section 4

The Operational Utility of Optimized Tactical Satellites

We have now completed the section of this study that dealt with explaining the many orbital and sensor constraints on satellites in circular LEO and magic orbits and determining the absolute best performance that can be obtained from satellites by optimizing their orbital placement. It is now time to examine space missions and compare the requirements placed on satellites 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.[68] 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 ISR, tactical warning and attack assessment, environmental monitoring, comm, and precision navigation and timing. This section of the study 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 1000 lb. 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 paper.

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 command 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 the cost of any of this required space support is not included in the cost calculations, as it is at the 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 like the XSS-11 or Chinese anti-satellite weapons, for example, would be a boon to those tasked with exercising both lethal and non-lethal shutter control on the space capabilities of hostile nations.[69] However, such control is unquestionably a strategic mission with immense political ramifications and global effects. Employing it may provide advantage to tactical warfighters on the ground—many strategic actions do—but the advantage will be secondary and 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, 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 sub-elements of space force enhancement individually below, using the circular LEO and magic orbits discussed previously as the 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 national command authorities through operational command centers such as NORAD’s Cheyenne Mountain Operations Center. This mission is currently performed from GEO by platforms such as the DSP satellites.[70] 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 primarily a strategic one.

The environmental monitoring mission provides data on space and terrestrial weather that could affect military operations. DMSP platforms are one part of the current implementation of this mission element.[71] Tactical warfighters rely heavily on DMSP information to help plan their actions. These satellites operate somewhat higher than the orbital regime envisioned for tactical satellites at a little less than 850 km, but weigh almost three times as much. Likewise, execution of the precision navigation and timing space mission element through the Navstar GPS gives warfighters an enormous edge on the battlefield. GPS birds orbit much higher at about 11,000 km, making an orbit about every 12 hours. [72] 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 sub-elements just discussed, the ISR and comm mission sub-elements 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. These constraints will be discussed first in relation to circular LEO and then magic orbits.

The primary limitation to all tactical satellite applications from LEO are 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 applies in varying degrees depending upon the FOR, but is a severe constraint even for the best-case horizon FOR. To counter this critical deficit, the goal orbit for the tactical satellite program should be changed from 100 NM to at least 500 km. As previously shown in the discussion of Figure 23 (p. 30), such an increase in altitude will cost at least five percent in the amount of mass that can be carried by the tactical satellite goal booster. However, the benefits of raising the altitude would seem to make such a trade worthwhile. First, it would make it much easier to keep the satellite in orbit for the full year goal lifespan of the satellite by significantly reducing the fuel it must carry to overcome the much smaller drag force at that altitude. It will also slow down the satellite and increase all of the FORs. Comparing Figures 9 and 10 (pp. 16-17) as well as Figures 14 and 15 (pp. 20-21), it is easy to see that these factors combine to approximately double or more the average contact time per day and drop the cost per hour overhead by at least a factor of two to three. Thus, the orbital mechanics portion of the mission constraints benefit greatly from the sacrifice of available mass. We must now examine how such an altitude boost affects payload performance.

While extending the lifetime, 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 discussed above, moving a satellite from a 100 NM orbit to a 500 km orbit decreases the signal strength by a factor of 7.2 for signals at nadir but only by a factor of 3.6 for signals at the edge of a comm/BFT FOR and 2.8 for signals coming from the horizon (SIGINT missions).

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 passive signal strengths quoted above requires increasing the radius of these antennae by a factor of between about 1.5 and 3, while the active antenna radii would have to be enlarged by factors of about five to seven.[73] The actual antenna sizes depend upon the required received signal strength, which is highly variable.

Optical apertures have to be similarly increased in size when satellite altitude is raised. In order to achieve a diffraction-limited 1-meter optical image across the entire 45 degrees off-nadir FOR from 100 NM requires a 0.13m (5.1 inch) diameter mirror while the same resolution from 500 km requires a 0.36m (14.2 inch) mirror. For infrared images, the mirror sizes are 0.32m

(12.7 inches) and 0.9m (35 inches) for the two altitudes.[74] Thus, unless the payload mass is extremely critical, it is recommended that the tactical satellite goal orbit for passive missions be raised to 500 km; the analyses in the remainder of this paper will assume that this more favorable case exists.

That said, it remains for us to determine whether the effects provided by satellites in these LEO orbits are valuable to a tactical warfighter. 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 warfighter, 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.[75] Even after boosting the altitude to 500 km over the mid-latitude target city of Baghdad, there are on average less than 10 seven-minute passes per day for the best-case horizon FOR SIGINT mission to less than 5 two-minute passes per day for the more restrictive imagery mission using a 45-degree-off-nadir FOR. The acquisitions cost of the coverage provided by such satellites is between $40K (SIGINT) and $430K (imagery) per hour, ignoring the expense of all ground operations required to control, communicate with, and exploit the data provided by the satellite.

As discussed above, to get 24/7 persistence from a SIGINT mission at 500 km, it would take a constellation of about 80 satellites. It is quite evident that even at the relatively inexpensive projected cost of the tactical satellite program, $20 million each, and their projected lifetimes, six months to one year, 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,[76] to provide what they call “tailored persistence.” Such persistence is obviously stroboscopic at best, providing a periodic flash of utility with large gaps of blindness in between. For only $100M per year acquisition costs, such a constellation could provide about 50 eight-minute SIGINT or about 20 two-minute imagery passes each day (see Tables 1 and 2, p. 3). On average, these passes would be followed by a half hour (SIGINT) or one hour (imagery) gap where no effects would be provided. The intermediate case, that of comm/BFT, would yield useable effects 40 times per day for six minutes per occurrence with a little over a half hour between passes. The costs per hour would remain the same as the single satellite case, as both the total coverage time and total cost increase linearly with the number of satellites in the constellation. In other words, one could get twice the coverage from a two-ball constellation than from a single satellite, but it would cost twice as much to buy it so the price for an hour of coverage would not change.

It must be noted again that in general the pass times for these satellites will be pseudorandomly distributed, with no apparent regular, set schedule between passes. Some will occur quite close together in time, while at other times there will be substantial gaps. This aspect of the timing of the passes will be detrimental to friendly mission accomplishment, as regular, predictable information would be much more relevant to a tactical commander. While seeming pseudorandomly distributed to a casual observer, the pass times can be very accurately predicted with commercially available software and data freely available on the Internet. While unsophisticated foes are unlikely to possess the wherewithal or central control necessary to effectively exploit such information, a moderately sophisticated enemy could devise simple counter surveillance strategies to defeat small numbers of such satellites, strategies such as comm security measures that ensure no useful transmissions are made during times when a

SIGINT bird was overhead or by ensuring that equipment and personnel are under cover when imagery satellites are in position.

On the other hand, even the relatively sparse constellation of five satellites discussed above would make such enemy comm 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 large-scale operations this frequently. Conversely, 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 these non-orbital platforms provide could be truly tailored to the pace of the battle instead of giving pseudorandomly timed stroboscopic flashes of insight.

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 comm capability. During an engagement, comm are needed when the warrior needs them, not when they are available. The tail can't wag the dog. Sporadic, pseudorandomly-timed comm capabilities will not support a tactical mission. The small duty cycles (having an asset overhead for less than 28 percent of the time for the favorable situation of a 5-ball SIGINT constellation at 500 km) prevent effective tactical use of sensors in LEO. Tactical commanders need the information available to them when *they* need it, not when the sensor is available to give it to them. They don't have the luxury of time to acquire and correlate multiple passes over the multiple days and weeks available to the strategic planner. The large gaps inherent in sparse LEO constellations, regardless of how good the sensors are, negate most of the tactical applications of these satellites. Even when the odd, opportunistic snippet of SIGINT information can be applied to a tactical operation, it is just as likely that another snippet from another theater would be just as useful. Having effects across multiple theaters is one of the hallmarks of orbital assets, and one that tends to make those assets strategic ones.

The reason tactical satellite proponents have devised the magic orbit is apparently to counter the LEO coverage problem just discussed. The relatively long hang times over large portions of the target's hemisphere 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, the orbital mechanics constraint. By moving further away from the earth in an attempt to slow down the satellite passes, this solution compounds the other constraint, the constraint on the payloads' ability to perform the mission.

It was previously recommended that the tactical satellite goal altitude be raised from 100 NM to 500 km in an attempt to similarly increase the contact time while keeping the negative effect on the payload to an acceptable level (an attempt that ultimately proved to be of little value, as the revisit rate for satellites even in higher LEO was still grossly mismatched to the timescale of tactical events). Even using the higher 500 km orbit as the baseline, the average magic distance from the target is 17 times further than the LEO orbit. As an example of a specific effect on payload performance 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, it would take 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 (see note 27). For this reason, it would seem impractical to use the magic orbit for conventional imagery applications.

Similarly, a comm or SIGINT antenna in a magic orbit would have to increase in size to be as sensitive to signals as its LEO counterpart. SATCOM on the move is a highly desired capability in the field.[77] Many people are familiar with satellite phones with their simple whip antennae that are easy to use. 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.[78] 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 on tactical satellites to about the required 200 m^2 to get similar performance to Iridium does not seem feasible. Of course it is possible for an engineer to come up with the appropriate matching of desired signal strength on the ground, satellite transmission power, and satellite antenna aperture; the difficult part is to do that within the mass budget of the available booster. 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 than today's less-than-optimal situation. 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* comm 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 UAVs are already controlled through satellite links. It seems feasible for these links to be through satellites in magic orbits. However, as we will see, 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 require some mitigating engineering design to ensure 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 COTS 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 is palatable, especially when we are reminded that a booster that can put 1000 lbs. into a 100 NM LEO orbit can only place a substantially reduced mass of 500 lbs. into the higher magic orbit.

It is a physical fact that the constraints imposed by orbital mechanics and those imposed by sensor limitations work contrary to each other. Attempt to get around one set of constraints and the limitations imposed by the other constraint become more dominant. Choosing an orbit that slows down the satellite pass to improve persistence ends up requiring huge increases in payload physical size (and a commensurate increase in payload mass) in order to maintain the standard of performance. Unfortunately, without an increase in booster size and cost, the ability to simultaneously raise the altitude *and* increase the payload mass is not possible. Thus, for satellites in other than very low altitude circular orbits, the cost rapidly escalates and the standard problem for space returns: the prices are so high that the assets become strategic and tactical commanders cannot afford to own and operate the assets they need. It's 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.

Several critical portions of the space support required for a real satellite system have been neglected in this study. The strain on an already overtaxed space control network that constellations of custom-launched small satellites would impose has not been discussed. Nor has any method for distributing the data collected by these satellites been detailed. The true value of a tactical reconnaissance program is heavily dependent upon actually using whatever data is collected. Presumably this statement would be true for a tactical satellite program as well. Such considerations would likely lead to bandwidth, mobile ground station, data correlation, data fusion, and analysis requirements. None of these problems will have cheap, easy solutions.

Finally, it must be reemphasized that this paper has consistently used very favorable assumptions with respect to FORs and sensor performance. For example, even the very expensive, specifically designed commercial imagery satellites do not normally take pictures much further than 30 degrees off-nadir; 45 degrees were allowed for. Weather and darkness were ignored. Time-optimized orbits were used which give the absolute best coverage and cost numbers possible. The assumptions of achieving perfectly executed programmatics and perfect system performance while meeting all cost goals are almost certainly overly optimistic. Even with these favorable assumptions, this paper has demonstrated that the ability of tactical satellites to deliver tactical effects is severely limited. Less optimistic (and more realistic) assumptions would certainly tip the balance further against the utility and suitability of tactical satellites for tactical applications.

As shown, there are severe physical constraints on satellites in circular LEO orbits and elliptical magic orbits that conflict with tactical mission requirements. It seems highly impractical if not impossible to perform tactically useful imagery, comm, SIGINT, and BFT missions within these constraints, especially if cost remains a consideration. Even tactical satellite proponents recognize the scale of the challenge when they write, "Given vast improvements in launch and spacecraft development costs and operations timelines, there is no foreseeable reason why theater ground units could not 'own' and control their own dedicated space constellations devoted to their specialized real-time tactical needs."[79] While on its face a true statement, the meaning of the word "vast" in this context may be underemphasized. As stated in the Scitor study referenced previously:

> Three 'Big Space' assets would do the job of 80 small satellites for a lot longer period of time. The sticker shock of the large assets would quickly be lost over the cost of numerous small satellites and the amount of maintenance required to keep them in orbit.[80]

Section 5

Common Arguments Prove the Point

A great amount of feedback on this study has already indicated that it seriously threatens a number of commonly held beliefs about tactical satellites and a number of ongoing funded programs. More of this is expected. However, a program should only have life when it contributes to the overall good. In the case of Air Force programs, the overall good means that a program contributes to helping prevent conflict, or should that goal fail, contributes to prosecuting a successful war as quickly and decisively as possible. As has been shown, unless constellations of hundreds of satellites are launched each year the tactical satellite program will likely not be able to provide its advertised tactical effects to the warfighter. It can, however, provide a limited number of strategic effects, some of which are currently performed by other systems. Whether a transformed "tactical" satellite program can do the functions of current systems more effectively is not within the scope of this study. The study merely points out that there may be ways to redirect the program toward more fruitful goals.

Is this study perfect and complete? Of course not. It is, however, as thorough a look at the whole story of the tactical satellite program as the author has seen in print. In an attempt to head off basic arguments against the conclusions of this study, several points that critics may bring have been anticipated and addressed here.

The first counterargument deals with FORs. Critics will correctly point out that the models used to calculate the average daily contact time for the satellites are based on single points on the ground, while even tactical engagements have some finite areas with which they are associated. This assertion is true, and accounting for city-sized or region-sized areas will increase the contact time over the numbers shown, lowering the gap time and cost per hour figures quoted above. The question that remains is how significant is this increase in performance? To get a ballpark estimate, let us look at the difference between the 30- and 45-degree-off-azimuth fields of view from Figures 3 and 4 (pp. 6-7). The additional area covered by the 45-degree-off-nadir FOR is a significant increase, with swath widths being 150 to 250 km larger and FOR areas being 75,000 to 600,000 square kilometers larger (100 NM and 500 km orbits). These sizes of these increases are much larger than a city and they greatly exceed the 20 km x 20 km spatial limits normally associated with the word "tactical"[81]. The difference between the performance numbers shown for these two FORs throughout this study could thus be indicative of the difference between calculations for a point and for a tactical area. Of course, as discussed in note 28, the 45-degree-off-nadir FOR is significantly larger than what most commercial imagery providers advertise for their for-profit ventures. Overstating the FOR capability of the sensors used in this study has more than made up for the "single spot on the ground" argument.

A second argument that could reasonably be made against this paper is that the satellites can be targeted against multiple locations on the ground, not just the selected target for which the data was presented. Again, this argument is true. The satellite does not park itself over a specific city. Except for special case orbits that do not maximize coverage, a satellite eventually will pass directly over every spot on the globe between the northern and southern latitude limits equal to its orbital inclination. It is free to perform its mission at any time along its ground track. This argument actually highlights a point obliquely hit earlier in the paper when Figure 22 and Table

3 (p. 30) were discussed. The biggest problem with satellites in LEO was shown to be the limited amount of time they spent over the selected target. To come up with even these meager contact time numbers, the orbit was optimized, matching inclination and target to give the best coverage possible. While it is true that locations at latitudes other than the optimal can also be targeted, the efficiency with which the satellite passes over these other targets is by definition less than optimal. Also, for a truly tactically-owned and tasked asset, and given the notion that the satellite would be launched to very narrowly described target areas and sensor configurations, all collections outside the tactical commander's area of responsibility should be considered opportunistic and would in no way improve the satellite's performance over the intended target.

From Figure 22, it is apparent that there is a narrow band of orbital inclinations around the optimal inclination for which the satellite spends an appreciable amount of time over the designated target. The width of the band is related to the width of the FOR; narrow FORs have narrow bands of inclination for which they are effective. The corollary is also true: once the inclination has been set by an actual launch, the satellite provides its most effective coverage at the optimal latitude and provides less and less coverage at latitudes further from the designated target. As has been shown, even optimized contact times over the designated target are very short and the passes do not occur with a tactically useful frequency, the main reasons for discounting use of LEO to obtain tactical effects. For targets at non-optimized latitudes, these passes would occur even less frequently.

However, the fact still remains that coverage at locations other than the target is possible. Satellites still do provide the potential for near-global access. It is possible and even likely that such a tactical satellite would be used at locations other than the primary target of interest (availability of power for multiple sensor repositionings and multiple taskings from a necessarily small bus and power supply system on a small satellite notwithstanding). All of these arguments against the calculations herein could be true and if so, they significantly decrease the cost per hour overhead of the satellite. However, once accepted as true, they also prove the assertion that the "tactical" satellite is indeed a strategic asset instead of a tactical one; it exerts influence and provides effects across multiple theaters of operation and is thus an asset that would not be owned by a single tactical commander.

An argument can be made that the method of optimizing satellite orbits used above is very mechanical and shows no understanding of how satellites are actually employed. From the very beginning of their training, physicists are taught to break problems down to their simplest, most basic parts. They then analyze those parts to discover fundamental limitations of the subsystem. Once the fundamental limitations are understood, the full system is reconstructed and the applicability of the subsystem limitations to the full system is determined. This analysis technique has been quite properly used in this paper, postulating that the most general orbit optimization technique to get tactical effects for the warfighter is to discover the absolute maximum time the asset could be overhead for any combination of altitude and orbital inclination. Once these best-case numbers are known, it is a relatively easy step to apply them to the frequently non-optimal orbits that are used in actual operations. Operational orbits were not chosen for use in the bulk of this paper for two reasons. First, there are a myriad of mission-driven orbits from which to choose, too many to be adequately examined within a relatively general paper such as this. Second, the goal was to show that even when the absolute best case orbit was chosen, the program still could not deliver tactically relevant effects.

As a specific example of how much worse the coverage could be using actual orbits, we can look at a highly capable commercial imagery satellite, Quickbird. Quickbird flies at 460 km. in a 97 degree inclination orbit to provide optimum lighting conditions for its day-only optical cameras that can look up to 51 degrees off-nadir.[82] **Error! Reference source not found.** lists the best-case 460 km, 51-degree-off-nadir and actual Quickbird contact times. In keeping with the goal to present the tactical satellite program in the best possible light, it is quite apparent that the method used in this paper implies significantly better performance and lower cost per hour overhead than actual implementations will likely deliver.

Orbit	Inclination	Contact Time (Day Only) (Actual Quickbird capability)	Contact Time (Day and Night) (Optimized number used in the analysis in this paper)	Benefit of the Doubt Factor (Factor by which the analysis in this paper exceeds actual, operational capability)
Bogotá Actual	97.25 deg	1 min 3 sec	2 min 5 sec	
Bogotá Optimized	0 deg	14 min 44 sec	29 min 28 sec	14.1
Baghdad Actual	97.25 deg	1 min 14 sec	2 min 29 sec	
Baghdad Optimized	36.5 deg	4 min 46 sec	9 min 32 sec	7.7
Oslo Actual	97.25 deg	2 min 9 sec	4 min 17 sec	
Oslo Optimized	63.5 deg	5 min 4 sec	10 min 7 sec	4.7

Table 4. Comparison of average daily contact times for the actual, operationally used orbit for Quickbird and the contact time used in this paper, a contact time based on an orbital inclination optimized for specific target latitudes. Shaded cells show the actual Quickbird capability (day only) and the capability cited in this paper (day/night). The benefit-of-the-doubt factor is the cited capability divided by the actual capability, showing the amount the analysis in this paper attempts to slant in favor of tactical satellites.

Another argument that could be made is that choosing to display the 100 NM/1000 lb reference orbit purposely sets up a straw man to be easily knocked down. This is not the case. There are numerous places in the literature that quote the reference orbit (see note 11). This orbit is the stated goal for the DARPA FALCON booster and does not require much less energy than the Space-X Falcon 1 can deliver. As a common reference point in the tactical/responsive satellite community, 100 NM/1000 lb is a valid basis for analysis, and one that has apparently been briefed to senior Air Force leadership.[83] In any event, the details will vary smoothly with excursions from this reference, and presenting results up to 600 km has bracketed most of the trade space and the broad region of validity for the overall conclusions should be evident. Similarly, the use of other numbers such as the one-year lifetime goal, $20 million acquisition cost goal for booster and satellite, 5-ball constellations, etc., are, as noted above, numbers used by tactical satellite proponents to sell the concept. They are used merely to illustrate what is actually possible when the full tactical satellite picture is presented in one place. Certainly there are a number of other equally convincing arguments that counter many of the conclusions of this study. It is envisioned that future revisions of this study will adequately respond to those arguments.

Section 6

Conclusion and Recommendation

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. Again, the myth of the tactical satellite is that they are tactical. Calling a dandelion a rose doesn't change its smell.

As former Director of the National Reconnaissance Office and Undersecretary of the Air Force Peter Teets has said:

> Small sats, microsats, have a role to play, there's no doubt about it. We shouldn't be saying, "Let's design small sats because they're small." We should say, "Small sats have a particular advantageous capability that serves some effect that we want to achieve." [84]

While this study has discussed a number of strategic things small satellites could do that might be advantageous to the nation, it has been conclusively shown that these satellites cannot provide effects useful to a tactical warfighter at a cost he can afford. To frame the problem with the thoughts of Mr. Teets, tactical satellites cannot serve the effect their proponents claim to want to achieve.

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 misnamed. 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 the mythical "tactical" satellite to compete for funding against other strategically-oriented programs. When they compete with and win funding against programs that actually do have the potential to serve warriors on the ground, they detract from Congress's intended budgetary goals. An inadvertent result of this misapplied funding could very well be unnecessary warfighter deaths and diminished warfighting capability when equipment that could have been available in the future is not there due to the opportunity costs associated with funding so-called tactical satellites. Continuing to fund "tactical" satellites out of budget lines intended directly to serve the tactical warfighter does a disservice to both the taxpayer and the warrior on the ground.

> The wise are not wise because they make no mistakes. They are wise because they correct their mistakes as soon as they recognize them.[85]

List of Acronyms and Abbreviations

ACTD	Advanced Concept Technology Demonstration
AFRL	Air Force Research Laboratories
AFSPC	Air Force Space Command
BFT	blue force tracking
C2ISR	command, control, intelligence, surveillance, and reconnaissance
COCOM	combatant commander
comm	communications
CONUS	continental United States
COTS	commercial-off-the-shelf
DARPA	Defense Advanced Research Projects Agency
DMSP	Defense Meteorological Satellite Program
DSP	Defense Support Program
FALCON	Force Application and Launch from continental United States
FOR	field of regard
FOV	field of view
GEO	geosynchronous earth orbit
GPS	global positioning system
ISR	intelligence, surveillance, and reconnaissance
JWS	joint warfighting space
LEHA	long endurance, high altitude
LEO	low earth orbit
LOS	line of sight
MAJIC	microsatellite area-wide joint information communications system
MORF	Magic orbit radio frequency
Mil-Spec	Military Specification
NM	nautical mile
NORAD	North American Aerospace Defense Command
ORS	operationally responsive space
SATCOM	satellite communications
SCOPES	space common operating picture exploitation system
SIGINT	signals intelligence
SMC	Space and Missile Systems Center
STRATCOM	US Strategic Command
TacSat	tactical satellite; refers to the specific series of satellite experiments being developed by AFRL
TENCAP	tactical exploitation of national capabilities
UAV	unmanned aerial vehicle
VMOC	virtual mission operations center

Biographical Sketch

Lt Col Ed “Mel” Tomme is the only combat pilot in the Air Force with a doctorate in physics. A Distinguished Graduate of the United States Air Force Academy (USAFA) in 1985, he attended pilot training at Reese AFB, remaining there for his first operational tour instructing in the T-37 Tweet. He was then selected to fly the F-4G Wild Weasel at George AFB; Spangdahlem AB, Germany; and King Abdul Azziz Air Base, Saudi Arabia. He holds a Masters Degree in Physics from the University of Texas at Austin and a Doctorate of Philosophy in Plasma Physics from the University of Oxford in England. Lt Col Tomme taught physics at USAFA for several years while also instructing in the T-3 Firefly and TG-7 Motorglider. He is the only officer at USAFA to ever have been recognized as both the Outstanding Academy Educator by the Dean and as the Outstanding Associate Air Officer Commanding by the Commandant. He currently works in Air Force Space Command’s Space Warfare Center at Schriever AFB, CO, serving first as Concept Development Branch Chief for the Air Force Space Battlelab and now as the Deputy Director of Air Force TENCAP. Championed by the Commander, Air Force Space Command, he personally briefed his concept for utilizing the near-space regime for military purposes to almost 200 stars and between April and November 2004, including the Secretary of the Air Force and Chief of Staff of the Air Force.

Acknowledgements

The author wishes to acknowledge the contributions of three individuals without whom this study would not have been possible. First, **Dr. Steve Carr** of The Johns Hopkins University’s Applied Physics Laboratory has been an inspiration, a sounding board, and an unindicted co-conspirator during the entire process of writing this paper. His advice and counsel have been invaluable. Second, **Mr. John Lundy** of the Space Warfare Center provided expert advice on the use of SCOPES and customized his personal satellite coverage models used to generate the results presented above for magic orbits. **Mr. Marc Herklotz** is the wizard behind SCOPES, and his assistance helped to get up to speed on visual orbital mechanics. He also produced source documents that were the basis for many of the ground trace figures in this paper. Finally, **Lt. Gen. (ret.) Gene Santarelli** was the original inspiration for this paper. He served as the senior mentor for the JWS portion of the Schriever III war game at Nellis AFB in early 2005. I discussed my beliefs about tactical satellites with him during the game and during the game out-brief presented to the Chief of Staff of the Air Force, having only a pair of coverage plots (plots that eventually became Figure 6 (p. 12) and Figure 17 (p. 23) in this paper) for support. He told me before I could go forward with radical conclusions of that sort I needed to “dot all of my i’s and cross all my t’s.” This paper is my attempt to do just that.

I would also like to thank the following individuals for their thorough reading of drafts of this paper: Mr. M.B. “Brown” Tomme, Jr., Ms. Diane Johnson, Mr. Don Olynick, Dr. Geoff McHarg, Capt. (USN, retired) Scott Witt, Lt. Col. Bob Newberry, Lt. Col. Sean Cavanaugh, Dr. Walter Buell, Col. Sigfred “Ziggy” Dahl, Dr. Barry Crane, Lt. Col. Jed Davis, Dr. Jeffry Anderson, Mr. Doug Urbaniak, Mr. Bill Zahn, Mr. Trace Tomme, Lt. Col Al Glodowski, Maj. Andrew Richardson, and Lt. Col. Gus Hernandez. I have incorporated many of their thoughts and believe this paper is a great deal stronger for their efforts.

[1] For example, see *AU-18, Space Handbook: A War Fighter's Guide to Space*, vol. 1, Prepared by Maj Michael J. Muolo, comp. by Maj Richard A. Hand, ed. Maj Richard A. Hand, *et. al*. (Maxwell Air Force Base, AL: Air University Press, December 1993).

[2] Comments, Gen John P. Jumper, Schriever III War Game Outbrief, Pentagon, Washington, DC, 26 July 2005.

[3] Ibid.

[4] Elite organizations such as Air Force TENCAP have 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. For example, Benjamin S. Lambeth, *Mastering the Ultimate High Ground*. (Santa Monica, CA: Rand Corporation), 2003, 45. "Airpower *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."

[5] James R. Wertz, "Coverage, Responsiveness, and Accessibility for Various 'Responsive Orbits.'" Paper RS3-2005-2002, *Proceedings of the Third Responsive Space Conference*, American Institute of Aeronautics and Astronautics, 25–28 April 2005, Los Angeles, CA, http://www.responsivespace.com/Papers/RS3%5CSESSION%20PAPERS%5CSESSION%202%5C2001-WERTZ%5C2001P.pdf (accessed 8 November 2005).

T. Ryan Space *et al.*, "Transforming National Security Space Payloads." Paper RS2-2004-2001, *Proceedings of the Second Responsive Space Conference*, American Institute of Aeronautics and Astronautics, 19–22 April 2004, Los Angeles, CA.

[6] Space *et al,* "Transforming National Security Space Payloads."

[7] Briefing, David Hardy, "TacSat Demo Status: Senior Leader Vector Check," AFRL, 22 Sept 2004.

[8] Elaine M. Grossman, "Air Force Wants to Create Small-Satellite Reserves for Crises," *Inside the Pentagon*, 6 May 2004.

Draft document, *Tactical Satellite Concept of Employment*. AFSPC, 28 July 2004.

Briefing, Maj Scott Cook, "TacSat/Joint Warfighting Space Demonstration Program," AFSPC Directorate of Requirements, 6 January 2005.

[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 approximately the capability to put 1000 lbs. in a 100 NM orbit. They can put lighter payloads into higher orbits as long as the combination of payload mass and orbital altitude are less than the energy available from the booster.

Briefing, Col. Rex Kiziah, AFRL, "Joint Warfighting Space," Schriever III War Game, Nellis AFB, NV, 8 Feb 2005.

Briefing, Capt. Beth Stargardt, AFRL Space Vehicle Directorate, "Tactical Space Employment." Joint Forces Command Joint Space Concept Development and Experimentation Workshop, Norfolk, Virginia, 31 March 2004.

[10] There is no all-encompassing “Tactical Satellite Program.” Instead, there are a number of research efforts being conducted by AFSPC/SMC, AFRL, DARPA, and others. The goals and parameters quoted throughout this paper are generalized numbers based on numerous sources cited below.

[11] The quoted orbital altitude is based on being able to launch a 1,000 lb. payload into a 100 NM orbit, the stated requirement for the DARPA FALCON program and the approximate capability of the Space-X Falcon 1 booster rocket. The mass-to-altitude requirement is a way of expressing the energy capabilities of the booster to laymen. It is the combination of mass *and* altitude that is important, not one or the other. A given booster only has the ability to deliver a certain amount of energy. It can boost a less massive payload higher or a more massive payload lower. The following sources state, in a variety of manners, the reference orbit altitude of 100 NM.

Ranny Adams “Rocketing to Space,” *Leading Edge: Magazine of Air Force Material Command*, August–September 2005, 12–13.

Wertz, “Coverage, Responsiveness, and Accessibility for Various ‘Responsive Orbits.’”

Cook, “TacSat/Joint Warfighting Space Demonstration.”

Briefing, LtCol Ed Herlick, AFSPC Joint Warfighting Space Division, “Joint Warfighting Space 101,” Apr. 2005.

“FALCON: Force Application and Launch from CONUS (Task 1 Small Launch Vehicle Phase II, Program Solicitation Number 04-05).” DARPA, 7 May 2004, http://www.darpa.mil/baa/pdfs/FALCONPhIISLVsolicitationFINAL(2).pdf (accessed 3 November 2005).

Speech, Gen Lance W. Lord, “Responsive Capabilities for Joint Warfighting Space,” Air Force
Association’s Air Warfare Symposium, Orlando, FL, 17 February 2005, http://www.peterson.af.mil/hqafspc/Library/speeches/Speeches.asp?YearList=2005&SpeechChoice=104 (accessed 3 November 2005).

Stargardt, “Tactical Space Employment.”

Briefing, Hardy, “TacSat Demo.”

[12] Wiley J. Larson and James R. Wertz, ed. *Space Mission Analysis and Design*, 3rd ed., (El Segundo, CA: Kluwer Academic Publishers, 1999), 985.

[13] “FALCON: Force Application and Launch from
CONUS.” DARPA. *Falcon Overview*, SpaceX Company, http://www.spacex.com/index.html?section=falcon&content=http%3A//www.spacex.com/falcon_overview.php (accessed 10 January 2006).

[14] “TacSat-2/RoadRunner Micro Satellite Fact Sheet.” Air Force Research
Laboratory, August 2005, http://www.vs.afrl.af.mil/FactSheets/RoadRunner.swf (accessed 6 November 2005).

“SpaceX Selected for Responsive Space Launch Demonstration under DARPA FALCON Program.” SpaceX Company, 20 September 2004, http://www.spacex.com/index.html?section=media&content=http%3A//www.spacex.com/press11.php (accessed 6 November 2005).

[15] Briefing, Kiziah, "Joint Warfighting Space."

Wertz, "Coverage, Responsiveness, and Accessibility."

[16] The reason that the cost per hour overhead is the same for a single satellite and a constellation is that when you launch the second satellite, you double your coverage time but you also double your cost.

[17] In 2004, the advertised baseline cost for a tactical satellite and launch was $15M. By early 2005 the price was being quoted as $20M to $30M. The current TacSat 2 will cost at least $50M, barring further problems.

White paper, "Operationally Responsive Space Experiment: TacSat-1," Department of Defense Office of Force Transformation, n.d.

Andy Pasztor, "Pentagon Envisions Operations with Small Satellites," *Wall Street Journal*, 26 August 2005.

Briefing, Kiziah, "Joint Warfighting Space."

"Joint Warfighting Space: Not (Just) an Idea, Not Yet a Program," *Inside the Pentagon*, 6 May 2004, 1.

Briefing, Col. Pamela Stewart, AFSPC Requirements Directorate, "Responsive Space Near-Term Plan," Air Force Scientific Advisory Board, Colorado Springs, CO, 27 April 2004.

Briefing, Kiziah, "Joint Warfighting Space."

Space, *et al*., "Transforming National Security Space Payloads."

Cook, "TacSat/Joint Warfighting Space.

[18] The results presented in Table 1 and Table 2 are based on quite optimistic fields of regard for the different mission types: horizon for SIGINT (signals intelligence), 5 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 comm 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 will be provided in the body of the paper.

[19] "VMOC Fact Sheet," US Army Space and Missile Defense Command. http://www.smdc.army.mil/FactSheets/VMOC.pdf (accessed 3 November 2005.)

[20] Based on the rudimentary free-space $1/r^2$ signal attenuation law. More detail on attenuation will be provided later.

[21] Iridium Satellite LLC, http://www.iridium.com/ (accessed 12 November 2005).

[22] This section will very briefly develop some very basic concepts of orbital mechanics. A much more detailed but still very readable discussion of this topic may be found in Jerry Jon Sellers, *Understanding Space: An Introduction to Astronautics*, 2nd ed. (New York: McGraw-Hill), 2000. A truly great work on a subject that will only become more important to the plans of warriors, *Understanding Space* should be required reading for all military officers. A more mathematical and rigorous discussion can be found in Roger R. Bate, Donald D. Mueller, and Jerry E White, *Fundamentals of Astrodynamics*. (New York: Dover) 1971.

[23] The speed of a satellite in a circular orbit around the earth in km/sec is expressed $\left(\sqrt{3.96 \cdot 10^{11} / \left(6.37 \cdot 10^{3} + h\right)}\right) / 1000$, where h is the altitude of the satellite above the earth's surface in kilometers. Similarly, the time it takes a satellite to complete an orbit of the earth in minutes is expressed $\left(4 \cdot 10^{4} + 6.28h\right) / (60s)$, where s is the speed calculated above.

[24] *Webster's Online Dictionary—Rosetta Edition*, s.v. "field of regard" and "field of view," http://www.websters-online-dictionary.org/ (accessed July 2005). A FOR is "the area of Earth that a sensor can access over its normal span of motion." This concept is commonly confused with a closely related term, FOV. A FOV is "the area of Earth [*sic*] that a sensor can collect from at any moment, but without moving the sensor." The subtle difference is that FOR encompasses everything that a sensor could see if it were moved on its gimballing system while FOV is a subset of FOR that describes what a sensor could see without being moved. For fixed sensors FOV and FOR are equal.

[25] Communications satellites need to be above the horizon by some specified angle to ensure that buildings, trees, and hills don't block them from view of the ground antenna.

[26] In reality, the signals can be detected from slightly beyond the horizon due to diffraction of the radio signal.

[27] For the very small angles typical for satellite imagery applications, the smallest feature size x that can be resolved by a circular aperture of diameter D at a range from the target R using an electromagnetic wavelength λ is approximately given by the formula $x = 1.22\, R\lambda/D$, showing the resolving power is linearly related to the range. George W. Stimson, *Introduction to Airborne Radar*. 2nd ed. (Mendham, New Jersey: Scitech) 1998, ch. 10.

[28] A survey of commercial optical imagery satellites revealed a number capable of off-nadir imaging. The following table summarizes their capabilities. Note that only one of these for-profit systems advertises an off-nadir capability of much more than 30 degrees, and then only at a substantially reduced resolution. The advertised revisit times are also substantially greater than one day even using the large fields of regard available at their altitudes of greater than 500 km, supporting our claim that the fields of regard we are using in our examples are generous.

Satellite	Orbital Altitude	Revisit Time with maximum look angle	Off-Nadir Capability	Source(s)
ARIES	500 km	7 days	30 deg	http://www.tec.army.mil/tio/ (accessed 16 May 2005)

CBERS	778 km	3 days	32 deg	http://www.tec.army.mil/tio/ (accessed 16 May 2005)
EROS B	600 km	3 days	21 deg	http://www.crisp.nus.edu.sg/~acrs2001/pdf/334BARLE.PDF pp. 1-6 (accessed 16 May 2005)
IKONOS	680 km	1 day (2 m resolution) 3 days (1 m resolution)	52 degree (2.1m resolution) 27 degree (1 m resolution)	http://www.tec.army.mil/tio/ (accessed 16 May 2005) http://www.spaceimaging.com/products/ikonos/index_2.htm (accessed 16 May 2005)
Quickbird	600 km	1-4 days	25-30 deg	http://www.gim.be/p/316D77DDB5208B62C1256B6D005464F9 http://www.tec.army.mil/tio/ (accessed 16 May 2005)
SPOT	832 km	1-5 days	27 deg	http://space.au.af.mil/primer/multispectral_imagery.pdf pp. 3-4 (accessed 16 May 2005) http://www.tec.army.mil/tio/ (accessed 16 May 2005)

[29] The earth is not truly spherical. The calculations below take into consideration its oblateness. What is ignored, however, is terrain. Unless the observer is on the top of a hill, actual contact times will be less than shown due to the terrain blocking a clear view of the satellite when it is near the smooth-earth horizon.

[30] All plots for circular orbits computed by the author using equations derived from M.W. Lo, "The Long-Term Forecast of Station View Periods", *Jet Propulsion Laboratory Tecommunications and Data Acquisition Progress Report 42-118*, April–June 1994 (Pasadena, CA: Jet Propulsion Laboratory) 15 August 1995, 1–14, http://tmo.jpl.nasa.gov/progress_report/42-118/118J.pdf (accessed 5 April 2006); and M.W. Lo, "Applications of Ergodic Theory to Coverage Analysis," Paper number AAS 03-638, *Proceedings of the American Astronautics Society/American Institute of Aeronautics and Astronautics Astrodynamics Specialist Conference*, Big Sky, MT, August 2003. With the exception of Baghdad, the cities were chosen solely on the basis of their latitude. No political or military implication is intended to be inferred from their inclusion in this paper.

[31] If the earth were not rotating, the plots would be exactly symmetrical about the 90 degree inclination line. The higher the satellite's altitude (and thus the closer the satellite's period is to the earth's period), the more significant the earth's movement becomes to the problem. Plots for higher altitudes thus are less symmetrical than for lower ones.

[32] In most cases, the optimized orbital inclination will be at or slightly larger than the target's latitude. The only case for which it is exactly equal to the target's latitude is for the theoretical case of a zero altitude orbit. As the satellite altitude increases above zero, the optimal inclination moves further away from the target's latitude, the magnitude of the shift being directly related to the size of the FOR. A close examination of the inclination versus altitude plots for Oslo and Baghdad will reveal this trend as altitude is decreased. When the plots actually display the altitudes down to zero, the behavior is quite apparent. Since the main point of this study is to discuss LEO satellites and not to discover esoteric orbital optimization trends it seemed more relevant to limit the plots to a lower altitude of 150 km.

The reason that the optimum inclination is generally larger than the target latitude is that the actual path the target appears to trace through the FOR is not a straight line but instead is a curve concave toward the equator. The longest average path this curve can be occurs when the satellite inclination is a certain fraction of a field-of-regard radius greater than the latitude.

When the target is near a pole or the equator and the FOR is large (large enough to significantly overlap the pole or the equator when the orbital inclination is the near the target's latitude), the generalization about the optimum latitude breaks down, as can be seen in the Bogotá plot. In those cases, the optimum inclination is zero (for near-equatorial targets) or 90 degrees (for near-polar targets). As altitude is decreased so that the FOR shrinks, the optimum latitude generalization once again applies.

[33] Of course, the corresponding latitude in the opposite hemisphere would receive exactly the same coverage, so technically there are two latitudes that are optimized for each orbit.

[34] This "truism" is actually only true to certain altitudes. Once you get high enough that you can almost see an entire hemisphere, raising your altitude further only marginally increases your contact time. Additionally, the absolute maximum contact time would be when a geostationary satellite is in view; that contact time would be 24/7. Moving higher than GEO 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.

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

[36] This assumption is reasonable for the smaller fields of regard attainable from LEO. A more detailed analysis of the actual curved path the target would appear to trace across the FOR, especially for an optimized orbit where the target latitude and satellite inclination are matched, will yield very slightly larger numbers for average and maximum path distances.

[37] The average chord of a circle is $2/\pi$ times (about two-thirds) its diameter.

[38] As the rotational speed of the earth varies with latitude, the denominator will not be exactly the number shown in Figure 12, but will be close. The earth's rotational speed has less than a 10 percent effect on the speed of the FOR over the earth's surface between polar and equatorial orbits.

[39] 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 midnight, for the next two weeks." The pattern of repetition is vastly more

complicated than that. For this reason, this study will use the term *pseudorandom* to describe the pattern of satellite passes over a spot on the earth.

[40] Diffraction effects allow waves to bend around objects. The longer the wavelength, the more pronounced the bending. We will ignore these effects in this paper as they only add very small amounts to the large FOR radii we are typically discussing. Electromagnetic waves are also refracted or bent as they pass through the ionosphere. This bending can be significant, especially at the lower radio frequencies. We will also ignore these effects in this paper.

[41] The discontinuities in the slope of the plots are due to the fact that pure equatorial and pure polar orbits are much more efficient for optimizing contact times when certain fractions of the fields of regard can cover the target from those inclinations. Once that critical FOR fraction is crossed, an inclined orbit becomes more effective. The slope change indicates the point at which the orbit goes from polar/equatorial to inclined.

[42] The data shown are based on a launch from the Eastern Range at Patrick AFB, FL to put a satellite into a Baghdad-optimized orbit.

[43] The mass numbers quoted here only involve energy differences between the two orbital states for the payloads. As some portion of the booster will likely be required to stay with the payload longer (and thus travel higher) in order to get the payload into the higher orbit, the energy required to carry the booster higher would not be available for the payload. The end result is that the actual mass that could be put into the 500 km orbit would be somewhat lower than stated.

[44] D.J. Knipp *et al*., "Simulating Realistic Satellite Orbits in the Undergraduate Classroom," *The Physics Teacher* 43, October 2005, 452–55. Exact values depend upon satellite mass, coefficient of drag, and cross sectional area.

[45] Briefing, Kiziah, "Joint Warfighting Space."

[46] Speech, Lt Gen James A. Abrahamson, LEHA conference, Air Force Research Lab in Dayton, OH, 28 October 2003. As an example of the urgent need for persistent ISR, retired Air Force Lieutenant General Abrahamson used a form of the word "persistent" 24 times in a 101-word section of his speech to the conference.

> No 'we just have to wait until the aircraft leaves' persistent; long endurance, comprehensive and persistent; persistent with change detection; long endurance persistent; not deterred by bad weather persistent; no 'it's time for the satellite, so hurry and get the tarp over the vehicle' persistent; 24 x 7 persistent; always active persistent; persistent; always there to stare persistent; persistent, persistent, persistent; long endurance persistent; long loiter persistent; persistent, persistent, persistent, persistent; no 'wait till the cloud comes over' persistent; persistent, persistent, persistent; if they want to operate, they have no cover: 24 x 7 persistence.

Briefing, Loren B. Thompson, *"I-S-R: Lessons of Iraq," Defense News* ISR Integration Conference, Alexandria, Virginia, 18 November 2003.

> [The] 3rd [Infantry Division] saw numerous shortfalls in its organic ISR and access to joint/national assets: [comm links] can't support fast [and] fluid ops over long distances; divisions need organic collection [and] processing capacity rather than relying on echelons above division; divisions need tactical SIGINT systems that can collect [and] jam across the spectrum; divisions must have UAVs at division and brigade level to provide near-real time imagery [and] targeting. [The] Marines [were] highly critical of ISR shortfalls. After crossing the line of departure, the division received very little actionable intelligence from external intelligence organizations. Intelligence sections at all levels were inundated with information. . . that had little bearing on their missions. The existing hierarchical collections architecture, particularly for imagery, is wildly impractical. Solution: procure [a] family of tactical intelligence collections platforms (ground [and] air) and decentralize collection.

COCOM's Feedback, Briefing, Hardy, "TacSat Demo." "Persistence needed for many capabilities; More comm and ISR in and out of crises (increased bandwidth/comm on the move)."

[47] Briefing, Col Steve Prebeck, "Joint Warfighting Space," AFSPC Science and Technology Forum, 1 October 2004. Several COCOMs interviewed for reaction to a comparison of different joint warfighting space options noted that satellites couldn't provide the persistence they needed.

[48] SMC/TD (Directorate of Development and Transformation) is one of the primary tactical satellite proponent groups in the USAF and has produced the ideas behind many of the briefings cited in this paper.

[49] Rich Tuttle, "Air Force Studies Unique Orbit for Projected Family of Small Sats (satellites)", *NetDefense*, 11 March 2004.

[50] Briefing, Byron Hays, *Responsive Space/Tactical Satellite Utility Analysis*, to Brigadier General William Shelton, Director of Plans and Policy, STRATCOM, April 2004

[51] *Encyclopedia Astronautica*, s.v. "Molniya-1", "Molniya-2", and "Molniya-3," http://www.astronautix.com/craft/index.htm (accessed 12 Nov. 2005).

[52] The earth is not perfectly spherical. This imperfection causes several orbital perturbations including the rotation of the apogee point of an orbit that the 63.4 degree inclination of the MAGIC orbit is designed to prevent. The discussions of these perturbations are beyond the scope of this paper. For a brief overview, see Sellers, *Understanding Space*, 273–276. A more mathematically rigorous treatment may be found in Lars G. Blomberg, "Micro-Satellite Mission Analysis: Theory Overview and Some Examples," *KTH Report ALP-2003-103*, Alfvén Laboratory, Royal Institute of Technology, Stockholm, Sweden, March 2003, http://www.ee.kth.se/php/index.php?actio

n=publications&cmd=download&id=3901&path=/php/modules/publications/reports/2003/&filename=3901.pdf&format=pdf (accessed 6 April 2006).

[53] For example, see Sellers, *Understanding Space*, 276.

[54] Space *et al.* "Transforming National Security Space Payloads."

[55] T. Ryan Space, "Point Paper on Magic Orbit RF (MORF)" (Unpublished), 20 Dec 2003. The acronym "RF" refers to the phrase "radio frequency."

Rich Tuttle, "Air Force Studies Unique Orbit for Projected Family of Small Sats (satellites)"

[56] Briefing, Hays, *Responsive Space/Tactical Satellite Utility Analysis*.

[57] As the Lo integral (M.W. Lo, "The Long-Term Forecast of Station View Periods") used for previous calculations is not applicable for elliptical orbits and orbits with repeating ground tracks, the calculations supporting the numbers presented for MAGIC orbits were derived from orbital propagation models written by the author and by Mr. John Lundy of the US Air Force's Space Warfare Center. Representative results were individually verified using AFSPC's SCOPES tool.

Relevant parameters used for the orbits are: apogee—485 km; perigee—7800 km; inclination—63.435 deg. As this study deals with global, average satellite coverages, specific epochs, right ascensions of the ascending node, and true anomalies were irrelevant. Data was generated for the satellite position every minute over a complete sidereal day at various latitudes for an arbitrary 45-degree longitude band (as the MAGIC orbit shows eight-fold symmetry, only one-eighth of the possible longitudes needed to be sampled). These data were then averaged across the latitudes to provide the mean values shown. Maximum and minimum values shown are the absolute maxima/minima at specific latitudes for any of the sampled longitudes.

[58] The argument of the perigee that maximizes contact time for our example city of Bogotá is actually 271.5 degrees, a slight shift from the generalization stated in the text. The argument of the perigee that would maximize contact time for southern hemisphere targets would be approximately 90 degrees.

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

[60] K. Endo "The Radiation Environment," http://radhome.gsfc.nasa.gov/radhome/papers/apl_922.pdf (accessed 28 October 2005).

J.E. Mazur, "An Overview of the Space Radiation Environment," *Crosslink: The Aerospace Corporation Magazine of Advances in Aerospace Technology* 4, no. 2, Summer 2003.

[61] Tom Page, "'Intelligent Action' Reaction," *Aviation Week and Space Technology*, 28 February 2005, 6.

[62] Briefing, Kiziah, "Joint Warfighting Space."

[63] John Kennewell, "Satellite Communications and Space Weather," Australian Government, Ionospheric Prediction Service Radio and Space Services, Space Weather Agency Web Site, http://www.ips.gov.au/Educational/1/3/2 (accessed 26 October 2005).

> Trapped radiation is much lower energy particulate radiation that must be considered for satellites that spend any significant time in medium altitude orbits. The Van Allen belts are in fact responsible for the bimodal distribution of satellites. Orbits below about 1500 km are mostly below the radiation belts, whereas geosats lie above them. Satellites in semisynchronous orbits (eg GPS) must employ radiation hardened components (particularly in the computer memory area) to survive for many years. So far, Molniya type satellites, with very elliptical orbits, are the only comsat to spend much time in the Van Allen belts, and even these transit the danger region fairly quickly on their way from perigee (where they are non-functional) up to their apogee where they spend most of their active life.

Flemming Hansen, "DTU Satellite Systems and Design Course: Space Environment" AAU Cubesat Website, Aalburg (Denmark) University Student Satellite, 21 August 2001, http://www.cubesat.aau.dk/documents/Space_Environment.pdf (accessed 26 October 2005).

[64] Retrograde (east-to-west instead of the normal west-to-east direction that takes advantage of going in the same direction as the earth's orbit) MAGIC orbits with inclinations of 116.6 degrees may be obtained from Vandenberg AFB, but only with a substantial 65 percent mass penalty that reduces the 1000 lb. reference to only 350 lbs. Wertz, "Coverage, Responsiveness, and Accessibility."

[65] One proposed method to avoid the launch azimuth limitation problem is to drop the booster out of the back of a large military transport at high altitude (several tens of thousands of feet) from an appropriate latitude/longitude that will allow direct insertion into the desired orbital inclination "Falcon Launcher Program," *Aviation Week and Space Technology*. On the surface, this scheme looks reasonable; however the limited availability of transport aircraft during the run-up to a crisis makes the solution more problematic in practice.

[66] *Air Force Tactics, Techniques, and Procedures Manual 3-1.28: Tactical Employment—Space* (U) Washington DC: Government Printing Office (GPO), 25 March 2005, 9-8–9-10 (SECRET). Cited paragraphs are unclassified. Inclination calculations from Larsen and Wertz, *Space Mission Analysis and Design*. The relationship between launch azimuth and orbital inclination may not appear to make sense to a layman at first glance. The function relating the two variables is quite complicated. As a general rule of thumb, it is not possible to launch directly into an orbital inclination that is less than the latitude of the launch location. For direct launches, the launch site must lie along the sinusoidal ground

track, a projection of the line between the satellite's position and the center of the earth along the earth's surface (see Figure 8 for an example).

Let us examine a pro-grade (easterly) launch from a northern hemisphere location. If the launch azimuth is due east, the ground track must be at the top of the sinusoid, so the orbital inclination will equal the launch location latitude (remember that the inclination angle matches the highest/lowest latitude the satellite flies directly over). If the launch azimuth is further north than due east, there are an infinite number of sinusoids that will contain the launch location, but all of them will have a maximum latitude greater than the launch location. They're heading north when they launch, so they must eventually go to a higher latitude. The same goes for launches with azimuths further south than due east. There are an infinite number of sinusoids that contain the launch location, but all of them are headed south, so they had to have come from further north than the launch latitude.

The only two cases where the relationship between launch azimuth and orbital inclination are easily understood are for due easterly (and westerly) launches, where the inclination equals the launch location latitude, and for due northerly (southerly) launches, where the inclination is 90 (180) degrees. All other launch azimuths will give results between these two extremes.

[67] Wertz, "Coverage, Responsiveness, and Accessibility."

[68] Department of Defense, *Joint Publication 3-14: Joint Doctrine for Space Operations*, (Washington, DC: GPO) 9 August 2002, ix–x, IV-5–IV-10, A-1–E-4.

[69] "XSS-11 Microsatellite Fact Sheet," Space Vehicles Directorate, Air Force Research Laboratory, Wright-Patterson AFB, OH, http://www.vs.afrl.af.mil/FactSheets/XSS11-MicroSatellite.pdf (accessed 6 November 2005).

"Rumsfeld Hits Two Home Runs." *Security Forum*, 01F 04, 12 January 2001, http://www.centerforsecuritypolicy.org/index.jsp?section=papers&code=01-F_04 (accessed 17 May 2004).

> Anyone who doubts that space is where this century's wars will take place would do well to take a look at the Chinese space program. The Hong Kong newspaper Sing Tao Daily reported last week on China's ground test of a scary satellite weapon called a 'parasite satellite.' This is a micro-satellite that could attach itself to just about any type of satellite with the object of jamming or destroying it if it received a command to do so. As Sing Tao put it, 'to ensure winning in a future high-tech war, China's military has been quietly working hard to develop asymmetrical combat capability so that it will become capable of completely paralyzing the enemy's fighting system when necessary by 'attacking selected vital points' in the enemy's key areas.

"China's Space Capabilities and the Strategic Logic of Anti-Satellite Weapons." Monterrey Institute of International Studies, Center for Nonproliferation Studies, 22 July 2002, http://cns.miis.edu/pubs/week/020722.htm (accessed 17 May 2004).

> There is a clear strategic logic for China's interest in anti-satellite weapons. Chinese media and military analysts have highlighted the growing importance of space in future warfare and paid increasing attention to U.S. military efforts to ensure future space dominance. As the Gulf War, the Kosovo conflict, and the recent Afghanistan campaign have demonstrated, the United States increasingly relies on space-based assets to support military operations. China's inability to compete directly with advanced U.S. technologies may lead the Chinese military to focus on asymmetrical methods such as ASAT weapons in an effort to counter U.S. military dominance.

[70] "Defense Support Program Satellite Fact Sheet," National Space Studies Center, http://space.au.af.mil/factsheets/dsp.htm (accessed 26 October 2005).

[71] "Defense Meteorological Satellite Program Fact Sheet," National Space Studies Center, http://space.au.af.mil/factsheets/ dmsp.htm (accessed 26 October 2005).

[72] "Navstar Global Positioning System Fact Sheet," National Space Studies Center, http://space.au.af.mil/factsheets/gps.htm (accessed 26 October 2005).

[73] Active sources generally are used to detect Doppler shifts to indicate target velocity. It is exceedingly difficult to detect Doppler shifts near nadir. The quoted antenna sizes discount the ability to use the antenna while pointed near nadir.

[74] Wavelengths used for these calculations were 400 nanometers (middle of the visible region) for the optical image and 1 micron for the infrared image. 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.

[75] John R. Boyd, *A Discourse on Winning and Losing.* Air University Library document number MU 43947, August 1987, (unpublished briefing notes and essays).

[76] Briefing, Kiziah, "Joint Warfighting Space."

[77] Briefing, Hardy, "TacSat Demo."

[78] "Catch a *Flaring/Glinting Iridium." Visual Satellite Observer's Home Page, 6 March 2002, http://satobs.org/iridium.html (accessed 26 October 2005).

[79] Space, *et al.*, "Transforming National Security Space Payloads."

[80] Briefing, Hays, *Responsive Space.*

[81] Department of the Army. *Field Manual 71-100: Division Operations.* (Washington, DC: GPO), 28 August 1996.

[82] Marc Herklotz, Developer of the SCOPES, Space Warfare Center, Colorado Springs, Colorado, correspondence with the author, January 2006.

[83] Peter Teets, "Space Programs Reflect War-Fighting Priorities," *National Defense Magazine*, June 2004, http://www.nationaldefensemagazine.org/issues/2004/Jun/Space_Programs.htm (accessed 5 November 2005).

Peter Teets, Statement by the Undersecretary of the Air Force before the Committee on Armed Services, United States House of Representatives, 25 February 2004, http://armedservices.house.gov/openingstatementsandpressreleases/108thcongress/04-02-25teets.html (accessed 5 November 2005).

Speech, Gen Lance W. Lord, given to the Air National Guard Senior Leader Conference, Phoenix, AZ, December 2004, http://www.peterson.af.mil/hqafspc/50th/Speeches.asp?YearList=2004&SpeechChoice=91 (accessed 5 November 2005).

Speech, Lord, "Responsive Capabilities for Joint Warfighting Space."

[84] "DOD to Launch Mini-Satellites," *Federal Computer Week*, 20 October 03.

[85] Orson Scott Card, *Xenocide*, (New York: Tor Science Fiction) 1991, 65.