Airborne and Space-Based Lasers:

An Analysis of Technological and Operational Compatibility

Kenneth W. Barker, Lt. Colonel, USAF

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Air War College

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The Author

Lieutenant Colonel Kenneth W. Barker, USAF, has been involved in research and development and the acquisition of high-technology systems for most of his 20 year Air Force career. Prior to entering the Air War College, he was assigned to the United States Air Force Academy and served both as Chief of the Astrodynamics Division in the Department of Astronautics and Chief of Honor and Honor Education Division in the Center for Character Development. In earlier assignments, Lieutenant Colonel Barker served as program manager, chief engineer, systems engineer, and test engineer for satellite, directed energy, and conventional munitions systems. As Program Manager and Chief Engineer for the Phillip's Laboratory's High Altitude Balloon Experiment, he was responsible for cost, schedule, and performance for this Ballistic Missile Development Organization Acquisition, Tracking, and Pointing experiment. As the ALTAIR satellite payload systems engineer, also at the Phillip's Laboratory, he was responsible for overall payload performance. As part of the Strategic Defense Initiative Organization's enabling technology efforts, Lieutenant Colonel Barker served as a laser beam control performance analyst for the Air Force Weapons Laboratory's Airborne Laser Lab, and managed the gyroscope test program testing nine gyroscopes from six international companies. Lieutenant Colonel Barker is a distinguished graduate of the Air Force Academy, Squadron Officer School, and Air Command and Staff College. He earned his Master of Science in Aeronautics and Astronautics from the Massachusetts Institute of Technology in 1982 and his Doctorate in Aerospace Engineering from the University of Washington in 199 1. In his current assignment as Lead, C- 17 Air Vehicle Integrated Product Team, Lieutenant Colonel Barker is responsible for all upgrade and modernization efforts for the C-17 Globemaster III.

Preface

Misunderstandings about the Airborne Laser (ABL) and Space Based Laser (SBL) abound. In the Fall of 1997, word spread that the Air Force had accepted "ownership" of the Space Based Laser program and would establish a program office at Air Force Materiel Command's Space and Missile Center in Los Angeles. Because the ABL had already been designated an Air Force program in 1992, standing up the SBL System Program Office meant the Air Force was now committed to two significant laser weapon programs.

Having spent several years involved with Strategic Defense Initiative Organization and Ballistic Missile Defense Organization programs, and concerned with the current climate of downsizing and shrinking budgets, I wondered how the Air Force would continue to advocate these two futuristic and costly weapon systems, especially since they are capable of performing the same mission. It soon became apparent that advocates and critics of these two programs had staked out their positions. The debate was (and still is) passionate, but left me with an uneasy feeling regarding the technical accuracy of the arguments. Especially troubling was the impression that ABL and SBL were technologically synergistic and that ABL was an important stepping stone to SBL. In my view, comments of this sort needed clarification so that the debate could proceed on a more factual basis. Accordingly, this study evaluates the compatibility of the ABL and SBL in terms of both technology and operational strategy.

I want to express sincere gratitude to Dr. William Martel and Col (Ret) Theodore Hailes of the Air War College's Center for Strategy and Technology (CSAT) for giving me the opportunity to conduct this research. I also want to thank my CSAT colleagues for taking the time to challenge my thesis, discuss the issues, and provide valuable advice regarding direction and content of this study. Finally, I want to express thanks to the ABL and SBL program offices and to the Director of Requirements of both the Air Force Space Command and the Air Combat Command for reviewing this paper and providing valuable comments.

Abstract

The Air Force is simultaneously pursuing both the Airborne and Space Based Laser programs. Under the impression that these two systems are synergistic and even that the ABL represents a logical stepping stone to the SBL, the Air Force has begun the process of advocating both programs, defending their funds, developing the required technology, fielding the weapons, and drafting the doctrine that will make them useful to the operational commands.

The purpose of this study is to assess the actual compatibility between the ABL and SBL by carefully examining both the technologies and operational strategies. Only by studying the similarities and differences between these technologies and the technical risks and challenges can the defense establishment gain a more detailed understanding of the compatibility of the ABL and SBL technologies. Only by examining the operational preferences revealed in each system's technical descriptions and concepts of operation will it be possible to understand the compatibility of the operational strategies for the employment of the A.BL and SBL. Once the facts about the actual compatibility between the ABL and SBL are known, the Air Force leadership will be better prepared to make the right decisions about the role of laser weapons in ballistic missile defense. This study hopes to stimulate further debate about how these technologies will influence the security of the United States in the twenty-first century.

There is no debate with the propositions that the ABL and SBL are both laser weapons that are capable of performing the same mission of theater ballistic missile defense. But despite the fact that these weapons are based on similar configurations inside their respective aerospace vehicles, it is essential to understand that the ABL and SBL systems are not sufficiently compatible to justify the claim that the programs are synergistic. In the case of operational strategies, the extent of compatibility depends strongly upon how the National Command Authority and military actually employ them. Separately, each provides a unique set of strengths and weaknesses, and arguably, each system's weaknesses are significant enough to compromise mission effectiveness. It is fortunate, however, that ABL's weaknesses are compensated by SBL's strengths, and vice versa. It is not surprising, therefore, that a combination of Airborne and Space Based Lasers working in concert would produce the greatest overall operational effectiveness.

I. Introduction

The Air Force is currently pursuing both Airborne and Space Based Laser weapons. [1] Perhaps due to the volatile and fragile politics that surround both programs, there is a tendency within the Air Force to claim that the two weapon programs share a high degree of technological and operational compatibility. Some within the Air Force suggest that the Airborne Laser (ABL) and the Space Based Laser (SBL) are similar, even synergistic, while simultaneously arguing that each offers unique contributions to missile defense. Some advocates believe that these programs are so compatible that pursuing both will benefit the development of each. Compatibility, rather than duplication, is the "official" Air Force position. This position is revealed in a variety of memos, point papers, and talking papers that describe a synergy between the ABL and SBL by suggesting that the ABL is a "stepping stone" to the SBL and that our commitment to pursue the SBL is dependent upon a successful demonstration by ABL. As this study will argue, however, it is not clear that terms Re "synergy" and "stepping stone" accurately describe the extent, if any, of the compatibility between these two laser weapon systems.

ABL and SBL share the same primary mission, which is to negate ballistic missiles during their boost phase segment of flight by using high-energy lasers.[2] Moreover, both systems share essentially the same collateral military missions. The Airborne Laser's collateral missions (referred to as adjunct missions) are, in order of priority, cruise missile defense, protection of high value airborne assets (HVAAs), suppression of enemy air defenses, and imaging surveillances.[3] By contrast, the SBL program's collateral missions (referred to as ancillary missions) are air superiority (counter air), space superiority (counter space, space surveillance), information dominance (ground surveillance, ground reconnaissance), and precision employment (force application).[4] The SBL program also describes the detection of space threats and the collection and assessment of astronomical data as potential non-military missions,. The reality, however, is that there is little difference in the ability of either ABL or SBL to perform the same types of collateral missions. The different names given to these collateral missions are predominantly a function of the different communities from which these ideas originate.

Both systems will become part of the nation's Theater Missile Defense (TMD) architecture, and thus offer "First-Tier" defense against theater ballistic missiles (TBMs). The ABL program expects to demonstrate a successful boost phase intercept of a TBM in 2002. A total of seven ABL aircraft are to be available to theater Commanders in Chief (CINCS) by 2005. The SBL program is currently negotiating various performance, schedule, and cost options with the Ballistic Missile Defense Organization (BMDO) and the Air Force. Given the Anti-Ballistic Missile (ABM) treaty, however, all of these options fall short of a fully operational capable (FOC) system, and deliver instead an ABM treaty-compliant sub-scale system that demonstrates the lethality of laser energy from space. The launch dates for these demonstrator options are between 2005 and 2014.

There is considerable debate within the technological, policymaking, and operational communities about the rationale for simultaneously pursuing both the ABL and SBL. Those in favor of simultaneous development argue that this approach makes perfect sense because the programs are synergistic, even when one considers that the ABL will become operational well before the SBL. They also argue that because ABL is a stepping stone to SBL, ABL reduces the overall risk for SBL. Furthermore, it is prudent to demonstrate the capability of destroying ballistic missiles while they are still in the atmosphere before moving into space. Indeed, the recent history of the United States is replete with examples in which the nation pursued and fielded more than one weapon system that shared a similar military mission. A prominent example is the F- 1 17 fighter/bomber and the B-2 bomber. Thus, advocates argue that the ABL and SBL programs are quite synergistic, beneficial, and even necessary.

Critics, however, remind us that the ABL and SBL have essentially the same primary and collateral missions and that the United States can no longer afford such extravagance. A second point is that the ABM Treaty currently prohibits the United States from fielding anti-ballistic missile systems in space, and thus raises the question of why the United States should pursue ballistic missile defenses if it cannot field an operational system. To these critics, the development of a demonstrator is the same as developing the weapon system, which raises concerns among some advocates of such defenses. For instance, the Air Force is managing both programs in parallel with other high-cost modernization programs (F-22, C-17, Space Based Infrared Radar (SBIR), MilStar, among other programs) in an era of shrinking acquisition budgets.

Those who believe that space deserves a separate service, in part because space assets would unfairly compete with air assets, could use this ABUSBL scenario as a case in point. Critics with an appreciation for the history of military technology also refer to both the ABL and SBL as "consecutive miracle" weapon systems because they require integrating several technologies, each of which represents technological leaps. In short, these critics could argue that having both ABL and SBL systems operational and available to a theater Commander in Chief (CINC) offers only marginal advantages. With these thoughts in mind, the purpose of this study is to assess the compatibility of the technologies and operational strategies of the ABL and SBL in order to clarify the debate about these programs.

To describe the compatibility between ABL and SBL technologies it is necessary to establish a framework for comparing and contrasting technologies. Despite the fact that ABL and SBL are both intended to negate ballistic missiles by projecting lethal laser energy onto the missile during its boost phase, this study shows that the fact that very different technologies are required or selected for each program diminishes the overall technological compatibility between the two systems.

To help understand the compatibility between operational strategies for ABL and SBL, it is important to grasp how the National Command Authority (NCA) and the military (Air Force) envision the employment of these weapons in theater operations. This study examines these different ideas on employment and concludes that the Air Force will be successful developing and deploying laser weapons only if both the ABL and the SBL programs are pursued with the intent of maximizing their compatible technologies and creating true synergy in their operational strategies.

II. Background

In spite of the overwhelming victory during the Persian Gulf War, the United States and its coalition partners were essentially defenseless against Iraq's unguided, short-range theater ballistic missiles (TBMs). Although militarily insignificant, SCUD missiles proved to be a potent political tool. In one incident alone, 27 American soldiers were killed when a SCUD hit a barracks in Dhahran, Saudi Arabia. Some post-war studies suggested that the Patriot missile defense system, which was based on a recently modified anti-aircraft surface to air missile, was only marginally successful in defending against the majority of SCUD attacks.[5] Fragments of Iraqi SCUDS, intercepted by Patriot interceptor missiles, fell on U.S. and allied territory. If Iraqi SCUD missiles had been armed with nuclear, biological, or chemical (NBC) payloads, even successful intercepts would surely have changed the nature of the war. The Air Force promptly took steps to rectify the situation.

With strong support from the Air Combat Command (ACC), Air Force Space Command (AFSPACECOM), Air Force Materiel Command (AFMC), and the highest levels in the Air Force (Secretary of the Air Force and Chief of Staff), the ABL System Program Office (SPO) was organized in 1992 under the auspices of AFMC Space and Missile Systems Center. The goal of the Airborne Laser program is to deliver seven operational laser weapons by 2005.

The ABL aircraft will be a stock (referred to as "green") Boeing 747 that is modified to house a megawatt class laser, transfer optics, and a nose-mounted, gimbaled transmitter/receiver telescope. Designed to operate at between 40,000 and 45,000 feet, the ABL will autonomously detect, acquire, track, and destroy TBMs that are launched within its lethal range.

The ABL program is based on nearly three decades of high energy laser and related technology research and development in the fields of atmospheric measurement, fire control, lethality, precision pointing/tracking, adaptive optics, and high performance optical coatings and components in the Department of Defense (DoD) and the Department of Energy. These technology development programs, which date back to the early 1970s, provided high confidence in the technology and a strong political base of support. Two key programs, the Airborne Laser Laboratory (ALL) and the Airborne Optical Adjunct (AOA), demonstrated the technological merits of the concepts that are critical to the Airborne Laser system.

The current ABL program's operational requirements stem from the Theater Missile Defense (TMD) Joint Mission Need Statement of November 1991, and the associated Air Force TMD Mission Need Statement (October 1991), the Air Force TMD Concept of Operations (CONOPS) (February 1993), and the ABL Operational Requirements Document.[6] Collocated with the Phillips Research Site of the Air Force Research Laboratory (AFRL) at Kirtland AFB in Albuquerque, New Mexico, which is the Air Force's center for directed energy research, the ABL program office continues to fund technology development with the Phillips Laboratory, Massachussetts Institute of Technology's Lincoln Laboratory and FirePond facility. These development efforts are focused on the key areas of technological risk in the ABL program.

The ABL program funded concept designs with two competing contractors through the spring of 1997. In June 1997, the Air Force selected the Boeing/Lockheed-Martin team to complete designs, conduct the remaining risk reduction experiments, and deliver a less than fully capable demonstrator in 2002 and a total of seven operationally capable weapon systems in 2005.

The Space Based Laser program is based on a similar legacy of technology development programs. Originally envisioned as a defense against Soviet Intercontinental Ballistic Missiles

(ICBMs), SBL:s boost phase intercept capability is an attractive option because it avoids the daunting problems of attempting to intercept thousands of multiple warheads or submunitions that could overwhelm midcourse and terminal phase defensive systems. The Space Based Laser could provide the U.S. and its allies with defenses against such a barrage.[7]

Space laser technology programs originated with the Defense Advanced Research Programs Agency (DARPA) in 1977. A joint system-level study was launched in 1982 that combined the technical expertise that existed within DARPA, Air Force, Army, and Navy. In 1984, the Strategic Defense Initiative Organization (SDIO) became the executive agent and management authority for all SBL programs. By the 1990s, some of the original technology development efforts are coming to fruition, including the development of the Alpha laser, Large Advanced Mirror Program (LAMP), Large Optics Demonstration Experiment (LODE), Zenith Star and several acquisition, tracking, pointing, and fire control experiments including StarLab, ALTAIR, and the High Altitude Balloon Experiment (HABE). It is important to note that the Airborne Laser Laboratory was a prominent part of these development efforts during the first seven years of the SBL program. The next eight years (1984-1992) were lean for both SBL and ABL. In part because it was viewed as the most feasible of the two in the near-term, the ABL was the first to garner support when the Program Office was established in 1992. SBL took longer, but gained renewed interest from the Congress when the Hill mandated additional funding of $98 million, which brought the total SBL funding to $127 million in FY98.

The SBL concept referenced in this study involves a constellation of 20 satellites that orbit at 1300 kilometers. Employing a megawatt class laser, an eight-meter primary mirror, and high resolution visible and infrared sensor suite, the SBL will autonomously detect, acquire, track, and destroy ballistic missiles at ranges on the order of 4000 kilometers. The SBL provides continuous and essentially complete coverage of the globe with the exception of the polar regions. With the ability to provide continuous and instantaneous protection against ballistic missile threats, an SBL constellation represents a significant enhancement of U.S. operational capabilities.

Both the airborne and space based laser programs depend upon significant technological developments in the 20-25 years that preceded the establishment of these program offices. These efforts were designed and executed to meet the specific demands of the air and space operating environments for the ABL and SBL, respectively. Moreover, the operating environment drove design issues that are system unique and essentially irrelevant to the other (e.g., atmospheric compensation technology). Another question is the degree to which elements of the two programs are unique and irrelevant as well as common and compatible. The next chapter defines a framework for addressing that question.

III. Framework for Assessing Compatibility

The purpose of this chapter is to define a framework for assessing the compatibility of large weapon systems. This is an ambitious undertaking for several reasons. First, the word "compatible" can be used properly in several contexts. Webster gives the word two major definitions: 1) capable of living or performing in harmonious, agreeable, or friendly association with another or others, and 2) capable of orderly, efficient integration and operation with other elements in a system. Second, the word is often used inappropriately, as for example when two systems are described as compatible when they are not for reasons that relate to political, budgetary, or organizational agendas. A third reason is that the word is vague and often requires further explanation. When it is said that two systems are compatible, it could refer to operations, the interchangeability of spare parts, or even the commonality of software. If the idea of compatibility is not defined in a detailed fashion, it can mean everything and nothing at the same time.

The intent in this study is to define a framework to bound the idea of compatibility, and then to apply that concept to the technologies and operational strategies that are involved in the Airborne and Space Based Lasers. This framework employs a terminology and rudimentary scale (high, medium, low) to quantify the degrees of commonality that are enjoyed by the various levels of technology (components, subsystems, and system) and the operational strategies that are emerging for these weapon systems.

Technologies

In the case of technologies, compatibility will be assessed in two ways. The first is to examine each program's self-identified "major issues" in terms of its technical risks and major technical challenges. The second is to examine the similarities and differences of each system's technologies.

Technical Risks and Major Technical Challenges. Every new weapon system is replete with technical risks and challenges. A critical task for development programs is to identify the risks and challenges in these systems, and to properly define the proper experiments and demonstrations that will reduce risk. It seems reasonable, then, that a way of describing the compatibility between two programs is to examine each program's self-identified major technical risks and challenges. A common set of risks and challenges should indicate when two weapon system use or apply compatible technologies. For example, if two systems employ autonomous navigation and consider the demonstration of autonomy to be a major technical challenge, then both systems would likely identify a demonstration of autonomous navigation as a significant challenge for development. If this were the case, the ability to demonstrate autonomous navigation by one program could be accepted by the other program as a valid indication of risk reduction or proof of concept. In the case of navigation technology, the first program qualifies as a stepping stone for the second. While the absence of conunon technical risks and challenges between two weapon systems is not conclusive, it should indicate that there is some degree of incompatibility in the technologies employed by the two weapon systems. In other words, common technical risks and challenges are strong indicators of an underlying technological compatibility.

Similarities and Differences. Similarities and differences among the technological building blocks in a system, which range from component to system level, are another indication of compatibility. This includes degrees of form, fit, and function that render pieces of or knowledge about one component or system either useful, or not, in the design or manufacture of another. To use a simple example, a pop-up toaster and a toaster oven share significant technological similarities and therefore can be considered technologically compatibles.[8] By contrast, however, systems that share the same mission do not necessarily consist of compatible technologies (e.g., conventional oven versus microwave oven).

A more useful way of discussing similarities and differences and thereby technological compatibility is by using terms like traceable, scalable, leverageable, and synergy, or the phrases risk reduction, proof of principle/concept, and stepping stone. Each of these terms and phrases deserves some explanation.

The term "traceable" describes the relevance of one technology to another. For example, software modules tend to consist of algorithms or lines of computer code that control system-specific functions. Today's high-performance fly-by-wire aircraft are inherently unstable without a working stability augmentation system that is part of the aircraft's avionics. The stability augmentation systems in early aircraft are probably not traceable to those that are employed on modern aircraft because fundamental differences in flight dynamics, which result in unique aerodynamic modes, mitigate the relevance of early avionics. In this case, relevance can be defined both in terms of the physics addressed (aircraft flight characteristics) and how the avionics modify those characteristics (e.g., classical versus multivariable control theory and analog versus digital implementation).

The term "scalable" describes how directly the physical principles involved translate from one technology into another. For example, engineers often construct models of their final product, or critical elements of their final product, to demonstrate the efficacy of a design principle (e.g., loading). If the model properly reflects the intended principle, then the design can be scaled up to the final dimensions. In bridge building, the engineer may want to demonstrate a new material's ability to handle certain loads. If the model uses the same material with the same proportional loading, then the model is probably scalable to the real bridge. Even the material itself can be considered a scalable parameter if a different material's loading characteristics, when used in the model, also scale properly to a different material when used in the real bridge. The art and science of scaling depends on knowing the critical physical principles involved and the influence of other factors (that may or may not be replicated in models or experiments) on those principles.[9]

"Levera:greable" is best understood in the mechanical sense as the action of a lever. To leverage simply means to get more out than you put in. In this same sense, technologies, systems, and programs in general can leverage other technologies, systems, and programs by providing small investments in manpower, funding, and facilities, among others, that capitalize on the outcomes of another program.[10] It is important to note that traceable and scalable do not necessarily imply leverageable. To take the example of stability augmentation systems (SAS) in aircraft, the F- 16 Falcon is closer in flight dynamics to the F-22 than any other aircraft. In that sense, its SAS is highly traceable to that used in the F-22 (digital multivariable control). However, the decision to use digital multivariable control for the F-22 represents only a fraction of the cost to implement that technology, and does not include the costs involved in merging the specific SAS for the F-22 with its larger avionics along with test. Thus, a plausible argument is that the F- 16 SAS is highly traceable but only minimally leverageable.

"Synergy" is possibly the most overused and misused word among engineers and program managers. Synergism comes from the Greek word sunergos, which means to work together. As long as two things work together, it is commonly said that there is synergy between the two. This is not, however, the best or most precise definition of the word. Webster defines the word to mean the action of two or more substances, organs, or organisms to achieve an effect of which neither is individually capable. In other words, the intent is not just to produce a greater effect, but to generate a fundamentally different effect. To illustrate, precision bombs permit the destruction of targets at costs that are lower than with unguided bombs. Stealth allows aircraft to be nearly invisible to radar. The employment of precision bombs with stealth aircraft produces a combined effect that neither technology alone could achieve on its own.

The notion of synergy is often used in new developments, especially when those developments are based on unproven technologies. The idea is to perform experiments or tests using elements of a larger system in order to reduce the risk that one element or subsystem will cause expensive failures or delays in the development and operation of the larger system. The necessary risk reduction events can be outlined on the milestone charts in development programs, which are designed to show the paths, whether serial or parallel, that lead to the final goal of producing a technology or capability. Each path is divided into discrete events. When events are deemed too risky, parallel paths are often undertaken that incorporate experiments or demonstrations for reducing these risks. Computer simulations are often useful risk reduction activities. End-to-end simulations, which are intended to represent the operation of the total system, are viewed as critical risk reduction endeavors in the most complex systems.

For the purposes of this study, the concepts of proof of principle and proof of concept are synonymous and will be discussed in terms of proof of concept. These phrases generally apply to experiments or demonstrations of technologies rather than individual pieces of hardware. There are some exceptions to this rule, generally in the software arena, and these will be noted when necessary. Proof of concept describes an event that proves something is necessary before something else can occur, particularly if that event has never occurred before. The Manhattan Project represents a proof of concept demonstration that paved the way to the use on August 6, 1945 of the atomic bomb on the city of Hiroshima. Never before had the concept of an atomic chain reaction been demonstrated and controlled as an explosion prior to the July 1945 detonation at White Sands, New Mexico. But it proved the concept. Another example is the first V-2 launch in October 1942, which proved the concept of ballistic missiles and ushered in the age of intercontinental ballistic missiles.

This phrase communicates a necessary or beneficial sequence of events that must occur and, more so than any of the previous terms and phrases, tends to be used to express the necessary order of events in technological and psychological terms. For example, the airplane was a necessary stepping stone to the space ship regardless of the fact that there are few, if any, key technologies that are common to the two systems. The physics of flight are different. In psychological terms, because humans were born without wings, people needed to see themselves safely off the ground in the air before human minds could grasp the thought of travelling in space. This is the psychological use of the phrase. The more technical use of the phrase is also valid. For example, propeller driven aircraft were necessary technological stepping stones to jet aircraft because the higher speeds achieved by propeller aircraft drove the development of the designs and manufacturing techniques in airframes that were necessary to support the higher speeds of jet flight.

These terms and phrases constitute the basic elements of a framework that will be employed to assess the similarities and differences and thereby the "compatibility" of technologies involved in the ABL and SBL programs. Each term or phrase will be quantified on a scale of low, medium, and high.

IV. Compatibility of ABL and SBL Technologies: Technical Risks and Challenges

Notwithstanding the immense technical challenge of integrating technologies that have never been integrated before, both the ABL and SBL programs have identified unique technical risks and challenges. In part, what makes these risks and challenges unique to each program is their operating environment. While the ABL operates in a wide-body aircraft in the atmosphere between 40,000 and 45,000 feet, the SBL operates in the harsh environment of space and close enough to earth to assure laser lethality and far enough away to maintain an affordable constellation. In both cases, the environment influences the technology.

ABL. The ABL program implemented a technology risk management program throughout its concept design phase. According to the Airborne Laser Cost Analysis Requirements Description, the five top priority areas of greatest technology risk for the ABL are integrating and testing the system on aircraft, actively tracking theater ballistic missiles, atmospheric compensation of the high energy laser beam, transition of track from missile plume to missile hardbody (hardbody handover), and the development of a flight-weight, high energy laser. Related to these risks, the ABL program office identified what they consider to be their major technical challenges. These are to characterize upper atmospheric turbulence including meteorological effects, evaluate phase-only adaptive optics performance in the presence of scintillation, demonstrate active tracking through turbulence, identify weight-reducing laser technology improvements, verify robust target damage modes, and define the software codes that are used for design analysis and performance prediction.

SBL. The top five prioritized technical risks for the Space Based Laser program are the development of the spacelift necessary to boost 80,000 pounds to 1300 km orbit; development of a deployable large primary mirror; development of a space qualified megawatt class laser; integration of the SBL technologies on a spacecraft; and an energy efficient ballistic missile kill. The major technical challenges for the SBL are to develop space qualified laser of shorter wavelength than SBL's current baseline laser, demonstrate a lethal laser from space, develop a heavy-lift booster, and develop a test and evaluation facility capable of precision alignment of deployable optics and performing complete test of the integrated system including the high energy laser, transfer optics, isolation systems, and beam expander.

Assessment of Compatibility. With the exception of unique aspects of platform integration, none of the identified technical risks and major technical challenges are common between the two programs. While this is not conclusive evidence that the two programs are not compatible, it indicates that ABL and SBL are deeply entrenched in their own unique technologies that share little commonality or compatibility with one another.

Some technical risks and challenges are common to both ABL and SBL, but not identified by both, for example hardbody handover and active track. The fact that ABL has moved further down the systems engineering trail than SBL may account for some disparity, and it is true that hardbody handover and active track have been recognized for years by both ABL and SBL communities as major concerns for both programs. SBL's failure to identify hardbody handover and active track as risks is more likely due to the fact that other risks in the programs had higher priority at the time.

The most telling evidence is revealed in the documented assessment of pertinent risk reduction programs for each system. Both the Airborne Laser Cost Analysis Requirements Document and the SBL Technical Requirements Document discuss in detail the relevant technology programs that are the basis for the overall confidence in the state-of-the-art technologies in these systems. In the eyes of the organizations and individuals that authored these documents, these technology programs are the true risk reduction and proof-of-concept programs for these weapon systems. From these programs, traceable and scalable technologies have been derived. ABL and SBL used their individual technology development programs in ways that were beneficial to themselves rather than to the other program. Throughout the years, both ABL and SBL invested (under sponsorship by DARPA, SDIOIBMDO, Air Force, etc.) in technology development programs. Primarily military or national laboratories and their respective contractors have performed these programs, which reduced the risk for both ABL and SBL. Prominent examples include the HABE integrated Acquisition, Tracking, Pointing, and Fire Control (ATP/FC) architecture and experiments that are relevant to both ABL and SBL. Another example is the adaptive optics work that was proven at the Starfire Optical Range at the Phillips Research Site, in particular the algorithm development portion that commands the deformable SBL mirrors. For a variety of reasons--program ownership, mutually exclusive funding sources, and pride in the ability to know, program, and direct one's own technology development requirements - neither ABL nor SBL has been eager to acknowledge the mutual benefit provided by some of these technology programs.

Similarities and Differences in ABL and SBL Technologies

Both the ABL and SBL systems can be divided into similar technological subsystems: laser device, beam director, beam control, acquisition, tracking, pointing, fire control, and battle management. The following section addresses the nature and extent of compatibility in these areas.

Laser Device

The purpose of the laser device is to generate the high-energy laser (HEL) with sufficient beam quality to cause catastrophic damage to the surface of a ballistic missile. The laser device consists of all the hardware, fuels or consumables, and the instrumentation and control necessary to perform this function.

ABL. The ABL laser device subsystem produces a multi-megawatt, 1.3um wavelength, chemical oxygen iodine laser (COEL) and the appropriate interfaces to the battle management, command, control, computers, communications, and intelligence ($BMC^4$1), beam control, and fire control subsystems. The ABL laser device consists of the fluids supply, oxygen generators, thermal management, gain generators, optical resonator, pressure recovery, and instrumentation and controls components. The laser device subsystem includes all of the optical train (mirrors, beam splatters, etc.) up to the aperture sharing element.

The ABL oxygen generator uses chlorine gas and basic hydrogen peroxide (BHP) to produce an excited form of oxygen called singlet delta oxygen, or energetic oxygen. The generator also produces the heat that is retained in the continuously recirculated BHP. The heat is transferred from the circulating BHP to ammonia using a heat exchanger for containing the BHP at all stages of salt saturation. A water vapor trap of cold hydrogen peroxide reduces the water vapor to a very low pressure of I torr (1 torr = 1/76O atm=14.7n6O lbs/in2). The final task of the oxygen generator is to transfer the energetic oxygen flow through a 90-degree bend to the gain generator.

In the gain generator, the subsonic oxygen flow is compressed and expanded by a bank of nozzles. After the nozzles create a supersonic oxygen flow, a mixture of iodine and helium in injected into the oxygen stream, and the resulting gain is extracted from the optical cavity using a negative branch optical resonator. The 6 torr cavity pressure is maintained by the pressure recovery system which recovers the low cavity pressure to the outside ambient pressure (141 torr at 40 kft and 197 torr at 33 kft).

The optical resonator is mounted on two benches and connected to the gain generator by beam tubes. Inside the resonator are six optical elements for extracting photons. Here are nine optical elements, including the HEL deformable mirror, in the external optical train that directs the laser photons to the beam control subsystem.[11]

The pressure recovery system uses a diffuser and an ejector to recover to atmospheric pressure. The combined laser and pressure recovery system gases are exhausted out the bottom of the aircraft.

The fluid supply system contains the tanks and plumbing for the storage and transport of laser fuels (consumables) consisting of BHP, chlorine, helium, nitrogen, iodine, hydrogen peroxide, JP-8, and ammonia. The fluid supply system and thermal management system supply all the fluids (gases or liquids) to the laser device.

SBL. By contrast, the laser device subsystem currently envisioned for the SBL weapon system, called the laser payload element, will be designed to produce a multi-megawatt, 2.7gm wavelength, hydrogen flouride (HF) laser and the appropriate interfaces to the BMC4I, beam control, and fire control subsystems. [12] The SBL laser payload element will consist of the gain generator, the optical resonator, and the reactant storage and feed subsystem, instrumentation and control subsystem, thermal management subsystem, and the low energy laser subsystem.

In the gain generator, flourine and hydrogen react in the central combustion region, are mixed with helium carrier gas (the diluent), accelerated to supersonic velocities and cooled as they pass through the primary nozzles. Ile fluorine-atom-rich primary flow is then mixed and reacted with hydrogen, which is injected into the primary flow through wedge-shaped structures across the exit of each primary nozzle. The reaction of the fluorine atoms and the hydrogen produces the laser gain medium that contains vibrationally excited hydrogen fluoride. The cylindrical gain generator produces a thin annular region of excited hydrogen fluoride molecules carried in supersonic helium flow (the laser gain medium). The laser photons are extracted from this gain medium.

The SBL's optical resonator will be specifically designed to efficiently extract photons from an annular gain medium producing a high quality, temporally stable output beam. [13] Since the laser operates in a near vacuum environment, no pressure recovery system is required.

The fluid supply system, referred to as the reactant storage and feed system, stores all of the reactants and other consumables. Most reactants will be stored as cryogenic liquids, except the helium, which will be stored as a cryogenic, supercritical fluid. This requires that there be an active cryogenic refrigeration system on the SBL satellite.

Assessment of Laser Device Compatibility. Given the fundamental difference in basic technologies at the lowest component level, the ABL laser device subsystem is not traceable, scalable, or leveragable to the SBL laser device. ABL's 1.3 Vm oxygen iodine laser uses different laser fuels, operates with a different laser gain medium, uses a different gain generation process, different injection, cooling, and pressure recovery processes than does SBL's 2.7Vm hydrogen flouride laser. Except for the oxygen generator, which the SBL laser payload element does not use, only the purpose of each laser device subsystem is similar (gain generator, optical resonator, etc.). The technologies exploited and the engineering and integration requirements differ significantly.

Consequently, efforts to develop the laser device in the ABL do not constitute credible risk reduction or proof of concept efforts for the SBL. The implication is that the ABL laser device is not a stepping stone toward a workable SBL laser device. Given that the same contractor (TRW) is developing both the ABL COIL and the SBL Alpha laser devices, some development synergy exists in the form of sharing ideas, progress, and facilities, but the overall compatibility between the two programs is low.

Beam Director

The beam director, which is the principal optical transmitter and receiver, has two purposes. As a receiver, it collects incoming optical signatures and transfers those signatures to the optical beam train. The optical train diverts different signature wavelengths to appropriate sensors for ATP/FC and beam control. As a transmitter, it takes the smaller diameter HEL, generated by the laser device, expands it to its appropriate larger diameter, and directs the HEL to the target. The key hardware element is the primary mirror that is part of the telescope assembly. Additional hardware is necessary to house the telescope within the beam director and point the entire assembly to the target.

ABL The ABL beam director is a nose-mounted, turret-housed, gimbaled telescope with a 1.5m diameter primary mirror. The beam director (or expander) expands the 25cm diameter (roughly circular) incoming high power laser beam into a 1.5m diameter outgoing beam and directs it at the intended target. The beam director also acts as a receiving aperture that collects return passive and active target signatures for tracking, collects returns for atmospheric compensation, and processes other signatures and images for target kill assessment.

The turret assembly, which consists of the turret ball and roll cylinder, lies just inside the bulge in the aircraft's nose. The turret has a 3.62m outer diameter and is separated from the airstream by an aerodynamic window. The window protects the beam director and acquisition sensor from the airstream and provides a smooth aerodynamic interface between the airstream and the turret to minimize buffeting and optical boundary layer effects. The HEL passes through this aerodynamic window when exiting the beam director, which has some deleterious effects on the quality of the outgoing HEL beam. The turret has roll-yaw and yaw-pitch gimbals to provide a wide field-of-regard in azimuth and elevation. Roll-yaw is used to perform the coarse positioning of the beam director, and yaw-pitch is used for fine positioning. Both coarse and fine pointing are controlled by the ATP/FC system and the beam control system.

SBL The SBL beam director is located in the forward part of the satellite and houses an 8-12m primary mirror. [14] The beam director expands the 25cm diameter incoming high-power laser beam into 8m diameter outgoing beam and directs that beam to the intended target. The beam director also collects return target signatures and images for tracking, surveillance, and imaging. Interspersed across the primary mirror are holographic gratings that sample the HEL beam to assess the quality of the outgoing beam. SBI's adaptive optic subsystem, supported by the deformable mirror inside the laser payload element's optical resonator, applies phase and jitter corrections to the BEL prior to entering the beam expander.

The beam director is held together structurally by composite truss legs that are 10- 15m in length. The truss resembles a cone with the large primary mirror aft and the smaller secondary/focus mirror near the front. The entire assembly is covered by shrouds to protect sensitive optical elements against inadvertently capturing sun glints or direct sunlight as well as protecting the optical surfaces within the assembly from space debris. The beam director is articulated with respect to the spacecraft body by the use of magnetic actuators. Commanding the beam director assembly to move with respect to the aft/spacecraft body is only done when optical line-of-sight motion is required outside the field-of-regard of a smaller, lighter optical element (e.g., fast steering mirror) within the optical beam train. Within the beam director assembly there is a separate aperture acquisition camera that is used for coarse track (discussed in the ATP/FC section).

Assessment of bean Expander Technology Compatibility. Differences in operating environment, range-to-target, and HEL wavelength determine the fundamental and major differences in the beam director technology for the ABL and SBL. ABL's beam director is relatively small and housed in the nose of an aircraft inside a gimbaled turret behind an aerodynamic window. SBL's beam director is between five and ten times larger, which alone creates significant technology differences in the two systems. The technology to place the substrate for a 8m primary mirror, grind it to within required tolerances, and then embed holographic gratings is not the same as the technology that is necessary for building a 1.5m mirror. The differences are so significant that some optics manufacturers capable of 1.5m fabrication generally do not have the capability to fabricate the larger 8-meter design. While the technologies are to some degree traceable, they do not scale easily, and in the case of substrate grinding, these technologies do not scale at all.[15]

When SBL's beam director is re-positioned, the surrounding truss assembly sways and vibrates. This ability to conduct rapid re-positioning generates significant vibration within the weapon. Ensuring that vibration does not transmit onto the incoming images or the outgoing laser is generally beyond the ability of standard optical vibration correction techniques (steering mirrors, etc.). [16] ABL turret/gimbal vibrations, while significant, are less challenging than SBL beam director/truss assembly vibrations.

It is understandable, therefore, why the SBL program has no interest in ABL's beam director technology or any of its fabrication, test, or integration experiences. SBL architects perceive little to no leverage to be gained from ABL beam director technology. With practically no commonality in fabrication, test, or integration, and certainly none as valid as that already in hand with SBL's own technology development programs (Alpha-Lamp Integration program), ABL's beam director is not a proof-of-concept for SBL and offers little to reduce the overall risk for the SBL program. No synergy exists between these two technologies and thus overall compatibility is low.

Beam Control

Beam control corrects and stabilizes the HEL against the disturbances that vibrate or distort the laser beam before it leaves the beam director. The

optical beam train is also stabilized against these disturbances, which ensures a stable incoming optical path for high precision tracking and imaging. Beam control systems consist of optical elements (steering mirrors, deformable mirrors, beam splatters), actuators, vibration isolation devices, low power alignment and boresighting lasers, inertial reference units, sensors, and control algorithms. Beam control and acquisition, tracking, pointing, and fire control- are highly interdependent, and in some cases there is no clear delineation between these functions. The fact that the ABL uses a shared aperture system and the SBL plans to use a separate aperture system is responsible for some of this ambiguity. [17]

ABL. The ABL's beam control system serves three basic functions. The first is to align and stabilize the optical line-of-sight from the beam director

to the laser device's optical resonator; the second is to perform high Fidelity track on targets designated by the battle management system; and the third is to measure and correct phase disturbances that distort the laser.

ABL has several sources of vibration, or jitter, that couple into optical elements and compromise a steady line of sight: aircraft dynamic flexure, aerodynamic buffeting of the turret/beam director, aircraft turbulence, and a vibration-rich "rocket-motor-like" laser device with accompanying high-level acoustics. Line of sight stabilization isolates precision optical elements from such a vibration-rich environment. Dynamic alignment keeps the optical elements "lined-up." ABL uses both passive and active isolation technologies in a four-tiered alignment and stabilization system.

The first tier consists of passive isolators (shock absorbers) that attenuate high frequency (>10 Hz) disturbances. The turret/beam director and the optical benches that support individual optical elements are mounted on passive isolators. Sound absorbing materials that damp acoustics, especially near the laser, are also included. The second tier handles low frequency vibrations and is controlled by active control loops consisting of low-power diode laser sources, sensors, and laser beam steering mirrors (known as "beam walk mirrors").

Any residual line of sight disturbances are further attenuated by the third tier, which consists of two active jitter control loops using components similar to those in tier two but with three additional technologies: high bandwidth

>500 Hz) steering mirrors, an aperture sharing element, and the Inertial Psuedo-Star Reference Unit (IPSRU). The IPSRU generates a near-inertially stabilized low power laser beam, projects it through the beam director, through the optical beam train, and to the IPSRU sensor that is located on the low power side of the aperture sharing element. The stable "jitter-free" IPSRU beam picks up jitter from the optical elements in its path. The total beam path jitter, sensed by the IPSRU sensor and attenuated by the high bandwidth steering mirror, is reduced to the low levels that are necessary for actively tracking ballistic missiles.

The final tier of alignment and stabilization is performed in concert with ABL's second beam control function, which is active fine track, that is known as the common path common mode (CPCM) fine track loop. When the low power track illuminator beams are stabilized on the nose of the missile, the beam director collects the reflected laser energy and transfers it into the optical train to the active fine tracker. The low power illuminator laser is made up of five solid state, near infrared lasers, which generate five individual beams. The beams exit the beam expander from five different sections of the primary mirror and take slightly different paths to the target. With this approach, atmospheric scintillation is averaged out and the beam will illuminate the target in a more uniform manner. The return reflected laser light is focused through the beam director and the optical train onto the target tracker. At the same time, a fraction of the laser beam that passes by the aperture sharing element is reflected into the CPCM's HEL tracker. The HEL tracker is a separate sensor, but performs similarly to the target track sensor. The CPCM track processor computes the difference in tilt between the two signals and puts the opposite of that tilt onto the beam cleanup steering mirror. The result of this process is to ensure that the high energy laser hits the target.

The last function of airborne laser beam control is to measure and correct phase disturbances that distort the HEL, which is called wavefront correction. The successful execution of wavefront correction is fundamental to the performance of the beam and represents the greatest technical challenge for the ABL. When a target is in fine track, another low power illuminator laser that consists of two interleaved high repetition pulsing lasers is pointed at the nose of the missile. Operating at a different wavelength than either the HEL or the five active fine track illuminator lasers, this laser, known as the beacon illuminator . laser, reflects from the missile nose and returns to the beam director. On its return trip, the beacon illuminator is degraded by the atmosphere, the airstream boundary layer outside the turret window, and the optical path internal to the ABL. The image is focused through the beam. director onto the CPCM's target wavefront sensor. [18] At the same time, a portion of the HEL beam is reflected back to the CPCM's HEL wavefront sensor. This sensor registers the wavefront errors on the HEL which are due to imperfect fabrication of optical elements, optical deformations due to thermal gradients, and errors due to beam path conditioning (attempts to prevent heating up the air inside the aircraft near the optical elements). The CPCM wavefront reconstructor computes the difference in waveftont errors between the two signals and places the opposite of that on the HEL using a defor,able mirror.[19] This process ensures that the HEL has maximum intensity on the target.

SBL. The SBf2s beam control system has the two key functions of aligning and stabilizing the optical line of sight from the beam director to the laser device's optical resonator, and second, of measuring and correcting the phase disturbances that distort the laser.

SBL's extraneous vibrations can be categorized as either aft-body or fore-body vibrations. Fore-body vibrations are primarily due to truss flex resulting from rapid re-positioning of the beam director assembly. Aft-body vibrations are primarily due to the laser device and the large cryogenic coolers that are necessary to maintain low temperatures in the laser reactant tanks. SBL uses both passive and active isolation technologies in a tiered alignment and a stabilization system that serves aft and fore-bodies independently and acts as an integrated system.

Both the fore-body and aft-body incorporate passive isolation technologies in their first tier. In the fore-body, adhesive materials with high vibration damping qualities are attached to the beam director's truss assembly to reduce as much high frequency jitter as possible. In the aft body, the laser payload element is mounted using space-qualified shock absorbing material to minimize the amount of high frequency vibrations transmitted forward to the fore-body.

Passive isolation measures are supplemented in both ends of the satellite with second tier active control loops. In the fore-body, multi-input/multi-output controllers, using combinations of accelerometers, velocity sensors, piezoelectric actuators, and voice coil actuators reject residual high frequency and middle frequency jitter. Second tier stabilization occurs in the aft-body, within the laser gain generator, using similar active control architecture, but it relies on optical measurements of and corrections to HEL vibrations using optical sensors and beam steering mirrors.

Residual aft-body jitter is further reduced by a magnetic actuator/isolator assembly. This assembly physically separates the fore-body from the aft-body, and is an integral part of the fore-body torquing mechanism. This third tier of stabilization is the first to consider the effects of fore and aft-body integration.

The final tier of alignment and stabilization handles high-frequency residual jitter across both the fore and aft-body using the Alignment Reference Transfer System (ARTS), the Alignment Annulus Assembly (AAA), and the IPSRU using optical sensors, turning flats, and high-bandwidth beam steering mirrors. As with the ABL, the IPSRU injects a highly stable low-power laser beam and accumulates jitter from the optical elements in the high power path, which are the same optical elements that the HEL interacts with on its way out. This beam traverses backwards from the primary mirror to the IPSRU sensor located near the laser payload element. Unlike the ABL, IPSRU injects its low power beam through the separate aperture ATP optical train but only up to the AAA on the main aperture through the ARTS. The ARTS consists of a set of optical tuning flats arranged like several periscopes placed end-to-end, which optically connects the separate aperture acquisition beam train with the HE-L line-of-sight. The AAA, mounted in the center of the primary mirror, injects stable, low power alignment lasers into the wavefront sensor as a reference for overall tilt on the high-energy laser. The wavefront sensor controls this tilt back in the aft-body optical beam train, which allows the ATP line-of-sight to be properly referenced to the HEL line of sight.

The second function of the SBL beam control is to measure and correct phase disturbances that distort the laser. Known as wavefront sensing and correction, this function does not represent the same degree of technical challenge as it does for ABL. The reason is that only phase distortions occurring on-board the SBL satellite must be measured and corrected.[20]

Outgoing wavefront sensing is a two-step process of sampling the wavefront and sensing the samples. Wavefront sampling is performed using the holographic gratings etched on the surface of the primary mirror. Small amounts of the HEL beam are diverted from these gratings through a hole in the secondary mirror where it forms an array of spots in the wavefront sensor. The wavefront sensor measures the distortion of the spot pattern that represents the HEL wavefront error. Outgoing wavefront correction is accomplished with a deformable mirror and is based upon phase conjugate calculations from the wavefront reconstruction software. Correcting the SBL high energy laser wavefront in this manner ensures maximum intensity on the target.

Assessment of Beam Control Technology Compatibility. The ABL and SBL manage beam control in generally the same fashion. Both consider line of sight alignment and stabilization as well as HEL wavefront sensing and correction for beam control. Unlike SBL, however, ABL considers active fine track to be a beam control function because the ABL operates as a shared aperture system that employs "return-wave sensing" technology for interweaving fine track with wavefront sensing. Despite this difference, ABL and SBL beam control involves a mix of both similar and significantly different technologies.

Some of the technologies that are necessary for accomplishing common functions are similar in the ABL and SBL programs. Examples include passive vibration isolation, active jitter control loops utilizing optical sensors, beam steering mirrors, inertial platforms, and wavefront reconstructors and deformable mirrors. These particular technologies are so similar, and in some cases nearly identical, that these are highly traceable to each other and thus leverageable between the programs. While both programs will claim the legacy for these specific technologies from their own technology development programs, overall risk can be reduced only if both programs stay informed of each other's successes and failures that occur in demonstrating these technologies and integrating them into the weapon systems.

However, some technologies are so dissimilar that little is in common between the two weapon systems. For example, SBL uses multi-input/multi-output active structural control technology on its massive beam director truss assembly to reduce low frequency vibrations. SBL also incorporates magnetic actuator/isolators to isolate its fore-body from its aft-body as well as the Alignment Reference and Transfer Systems that transmits alignment between the two. There is counterpart to these technologies in the ABL program. SBL also incorporates holographic gratings on its primary mirror for outgoing wavefront sensing, while ABL incorporates a much more complex five-beam track illuminator/two-beam beacon illuminator return path wavefront sensing technology. ABL also incorporates an optically complex aperture-sharing element. SBL has no such technology. In these cases, the technologies are so different that they are not traceable and certainly not scalable, and neither program can leverage anything useful from the other. Neither program reduces the risk for the other and no synergy exists between the two.

The common technologies between ABL and SBL tend to be those that involve relatively low risk - notably the technologies that are derived from each program's individual technology development programs. On the other hand, the higher risk technologies incorporated by both ABL and SBL tend to be those unique to each system. Therefore, although compatibility does exist among some beam control technologies, it primarily involves those with lower risks. Consequently, despite the fact that these low-risk technologies are traceable between ABL and SBL, very little real benefit is derived from leveraging these technologies between the programs, and very little synergy can be expected. The overall degree of compatibility between ABL and SBL beam control technologies is low.

Acquisition, Tracking, Pointing, and Fire Control

The acquisition, tracking, pointing and fire control process involves acquiring the target, tracking the target and handing it over to higher levels of precision, selecting an aimpoint, pointing the weapon system's optical line-of-sight to the target, performing mode control for the laser device and beam control system, and performing HI assessment. ATP/FC systems are highly integrated with beam control systems and, as discussed in the beam control section, ABL might consider a particular function under the purview of the ATP/FC system. At the same time, the SBL considers that same function under the Beam Control system, and vice versa.

ABL. The ATP/FC optical functions in the ABL are accomplished predominantly through the main aperture, which means that the ABL is a shared aperture system.[21] ABUs acquisition and tracking process begins with the widest field-of-view sensors mounted outside the aircraft fuselage and ends inside the aircraft on the main aperture's narrowest field-of-view tracking camera. Wide field-of-view surveillance sensors mounted around the ABL aircraft fuselage initially detect targets. Once detected, the battle management system passes the target's coordinates to the ATP/FC system, which initiates the pointing process by slewing the turret to the commanded position. The ATP/FC system then begins the process of handing over from its separate aperture acquisition sensor to the main aperture for coarse and active fine track.

"Hardbody handover" is the process of switching from passively tracking the missile's plume to actively tracking the missile body.[22] The process can be described as beginning when the fire control processor computer algorithms estimate the position of the missile body with respect to the plume using information from the laser range-finder and imagery from the missile plume. Using this information, the tracking illuminator lasers are pointed to flood the missile's nose. The tracking illuminator lasers create a spot on the nose that acts like a beacon for the active fine tracker, as described earlier in the beam control system section. When active fine track has been established, "hardbody handover" has been accomplished and an aimpoint for the HEL must be determined.

The most obvious criteria for the HEL aimpoint is to focus the beam on a vulnerable part of the missile body, which may be the pressurized fuel tank in liquid-fuel missiles. Another criteria that is unique to ABL's atmospheric compensation process is to align the aimpoint to the column of the atmosphere that is being compensated by the Beam Control's wavefront correction system.

ATP/FC mode logic describes the process of controlling the operation of both the laser and beam control functions. These include transitioning the beam control system from target acquisition to active fine track, turning on the beam control's tracking and wavefront beacon illuminators, transitioning the laser system from a low fuel flow rate "ready" mode to the full fuel flow rate "high power" mode, and either shutting down the laser and beam control systems or moving to the next target in the queue. Mode control also includes managing computer decisions for resolving anomalies, as exemplified by the loss of target track and abort indicators.

The final ATP/FC task is to assess target kill. As soon as HEL energy is placed on the target, ATP/FC sensors begin looking for indications that the missile has been destroyed. Indicators include sudden changes in the missile's velocity and acceleration profiles, sudden changes in the hot spot created by the HEL beam, and human operator observation of the coarse track sensor as it resolves the image of the disintegrating the target.

SBL. Since SBL's ATP/FC optical functions are accomplished almost exclusively through apertures other than the main aperture, SBL is referred to as a separate aperture system.[23] Similar to ABL, SBL's acquisition and tracking process begins outside the optical train with the widest field-of-view sensors and ends inside with the ATP/FC aperture's narrowest field-of-view tracking camera.

The SBL wide field-of-view acquisition camera performs the same detection function as the ABL surveillance sensors. Once a target is detected, the Fire Control system initiates the pointing process by slewing either the beam director or the entire spacecraft to the target position. Using the acquisition sensor, ATP/FC then begins a coarse track on the target's plume. Once stabilized in coarse track, Fire Control hands over this separate aperture acquisition sensor to the two-meter aperture for passive intermediate and active fine track. The hardbody handover and aimpoint determination processes described in ABL's ATP/FC section is generally similar to that employed by the SBL.

Mode control and kill assessment have similar objectives as ABL. The technologies include computer codes and algorithms that monitor certain events,. like pressures or signal intensities, and command other events, Re switching off the laser or retargeting the beam director. In these cases, technological compatibility is more determined by decision-making criteria than the types of hardware or software that are employed.

Assessment of ATP/FC Technology Compatibility. The biggest difference' between ABL and SBL ATP/FC technologies stems from the number of apertures used to accomplish the ATP/FC functions. Except for acquisition, ABL uses a single main aperture to gather incoming target signatures to perform wide field-of-view coarse track and the narrowest field-of-view fine track. ABL's main aperture acts as the outgoing beam director for four different lasers: the ranging laser, the track illuminator laser, the beacon illuminator laser, and the HEL. SBL, on the other hand, uses four separate apertures to accomplish essentially the same signature gathering and laser emitting tasks. This complicates the boresighting and alignment tasks for the SBL but simplifies the design and manufacture of optical elements. As an example, the SBL does not need the complex aperture-sharing element used on the ABL.

In effect, ABL has accepted increased complexity in some optical elements for the simplicity gained with fewer apertures. There is no obvious reason that both systems could not employ either shared or separate aperture architectures. However, the fact that ABL and SBL have chosen different architectures limits the compatibility of the technologies employed. For example, the boresighting and alignment technologies of the SBL (AAA and ARTS) are traceable to the AB L only in the sense that the IPSRU is a common element between the two. ABL's aperture sharing element is not traceable to SBL at all.

The preponderance of ABL and SBL ATP/FC technologies, however, are compatible. For example, ABL and SBL coarse track sensors "see" essentially the same phenomenon--a bright missile plume covering roughly the same area across the sensor surface with approximately the same geometric features. The specific sensor technologies, while traceable, are not leveragable because they are based on different materials. However, the signal coming from these different sensors looks the same to the signal processing algorithms. It is important to understand that these algorithms bear a close resemblance in the ATP/FC technologies used by the ABL and SBL. Much can be leveraged between the two programs and both should prove to be valuable risk reduction exercises for each other. While the synergy can be significant if there is significant coordination between the two programs, the overall degree of compatibility is medium to low.

Battle Management

The concept of battle management includes the overall command, control, communications, and coordination of the weapon system during all phases of operation. It also can include coordination with the overall theater battle management system.

ABL. The battle management, command, control, computers, communications, and intelligence system for the ABL includes a number of technologies: computer consoles with operational displays and controls, mission avionics, communications, navigation, and surveillance systems, target identification algorithms, self defense systems, mission data recorders, and related support software. ABL battle management encompasses five key areas: 1) detecting, tracking and prioritizing boosting TBM targets; 2) reporting target events and engagement results; 3) managing the health and status of ABL operations; 4) monitoring/engaging warning and self protection measures; and 5) maintaining theater situational awareness and connectivity to the Joint Force Commander.

The technologies that support battle management for the ABL are separated into two key subsystems: avionics and crew accommodations/personnel equipment. Avionics includes displays and controls, communications, navigation, target identification, surveillance, self-defense, and data recording. Crew accommodations/personnel technologies are driven by concerns about support for the aircraft crew as well as human factors engineering on-board the aircraft.

A range of communications and intelligence technologies make possible both internal and external communications. Internal connections allow ABL crewmembers to communicate and pass information, while external connections provide connectivity to theater assets for theater battle management, including the Airborne Warning and Control Aircraft (AWACS) and satellite communications (SATCOM), among others. The technologies include HF, VHF, and UBF radios for air-air, air-ground, and air-space communications. The appropriate frequency bands for high data rate communication support both voice and data, and wide band datalinks allow imagery transfer from intelligence, surveillance, and reconnaissance assets such as INMARSAT.

SBL. The battle management system for the SBL is responsible for target prediction (detection), target characterization (identification), constellation coordination, autonomous operations, and command processing. The concept of target prediction involves predicting target location at a particular moment and maintaining a target position database. Target characterization determines the critical characteristics of the target that are necessary for supporting a missile engagement, which includes the type of missile, probable location of the most vulnerable aimpoint, and the likely payload of the missile, among other considerations. Constellation coordination involves managing the timing of the activities and events that are associated with handing off the target from one satellite to another, avoiding satellites in lower earth orbits, and a number of self protection measures that will be required for the SBL. The SBL also must be able to operate autonomously on very short notice, and do so while not in contact with ground controllers or other SBL vehicles. Finally, command processing manages all of the command and control communications and datalinks that exist with ground stations.

The technologies supporting SBL battle management are performed by two main subsystems: the communications subsystem and the battle management computer hardware and software. The communications subsystem is responsible for the high quality real-time communications and data links that are essential for effective battle management. Communications tasks include receiving and transmitting command, telemetry, health and status of the SBL platforms, and mission data. Technologies include an S-band Space Ground Link System (SGLS) transceiver,[24] a Tracking and Data Relay Satellite System (TDRSS) transceiver,[25] a laser cross-link transceiver (for laser communications),[26] encryption/decryption equipment.

The battle management for the SBL is included within the larger SBL ground segment that is responsible for ground command, control, and communications with the SBL constellation and linking the SBL with theater battle management systems as well as on-board command and data handling. The ground segment, which provides peacetime and wartime control for the SBL system, includes all of the equipment that is necessary for performing constellation operations, mission operations, and launch and deployment operations. Primary and backup ground stations will be based in the continental United States, and there will be a transportable van for the theater operations.

The on-board command and data handling system receives, decodes, processes, coordinates, and distributes commands and data between all subsystems on the SBL satellite. Technologies include VME circuit card assemblies (driven from other space programs) packaged in radiation-hardened carbon/aluminum composite housing.

Assessment of Battle Management Compatibility. The unique operational environments and requirements for autonomy drive the battle management architecture and technologies for the ABL and SBL. While the ABL will be operated in a similar fashion as other high-value airborne assets in the theater, the SBL will be operated in a fashion that is similar to that of other communications and intelligence, surveillance, and reconnaissance (ISR) satellites. The SBL, however, will have a more intense system for command and control in view of the fact that it is designed to operate as the first weapon in space.[27]

For this reason, most of the technologies that support battle management for the ABL and SBL are fundamentally incompatible. For example, ABL communications and intelligence technologies employ frequencies and bandwidths that are typical for air-ground operations, while SBL technologies require frequencies, bandwidths, and error rates that are more appropriate for autonomous operations in space. To enable satellite-to-satellite connectivity, SBL uses laser communications, while ABL uses no such technology. To cite another example, ABL surveillance uses aircraft surveillance sensor technologies, which is a modification of a similar sensor used on the F- 14D aircraft, while the SBL uses a dual-telescope wide field-of-view infrared cameras that are derived from other space surveillance programs, such as Space Based Infrared Radar System, Hubble Space Telescope, and others. Finally, navigation and guidance technologies and avionics technologies are driven by the fundamental differences that exist in the operation of aircraft and satellites.

It is important to understand that the battle management for the ABL and SBL share similar functions and, therefore, should have some degree of similarity or compatibility in technologies. For example, ABL and SBL battle management both rely on computer algorithms to identify targets, coordinate the employment of multiple ABLs or SBLs in a military operation, and assess the likelihood of a ballistic missile kill. Although the ABL design currently does not incorporate algorithms to help discern different types of ballistic missiles, while the SBL plans to have that capability, the ability to identify friend or foe (IM is common to both ABL and SBL.

The computer-based parameters for making decisions, which enable the coordination of multiple platforms and control certain events on single platforms, are Rely to be based upon similar criteria for both the ABL and SBL. Criteria include the number of targets in theater, target's probable payload, time into boost phase, and target kill indicators, among others. The details on how these events are prioritized may be similar between the two programs.

Commonality also exists at the highest levels of the decision algorithms that are embedded in the battle management software. These algorithms employ criteria for making decisions, including handing over targets from surveillance to acquisition, cycling through various modes of laser and beam control operation, assessing probability of TBM El, managing overall command, control, and intelligence flow, and resolving anomalies, among others. A significant degree of commonality should exist within these algorithms as well as the simulations that are used to model and test the algorithms.

In summary, although the battle management functions of these weapons are similar, on a fundamental level most of the technologies used by the ABL and SBL are dissimilar and incompatible. On the other hand, software for determining the flow of critical command, control, and intelligence information and software that optimizes layouts for crew displays used in battle management architectures should be compatible.[28] Although ABL crews reside on the aircraft and SBL crews sit in fixed or transportable ground stations, the kinds of information shown on displays should be similar. The ABL and SBL programs can use this similarity for human factors engineering. Thus, when one considers these factors, the overall compatibility between ABL and SBL battle management technologies is quite low.

V. Compatibility of ABL and SBL Operational Strategies

This section evaluates the degree of the compatibility in the operational strategies for the ABL and SBL on two levels. The first is an examination of the operational similarities and differences as expressed in the operational concepts for each system, while the second is to understand the technological design and capabilities of these two weapon systems.

Operational strategies for weapon systems are said to be compatible when those systems can work together in an efficient and effective fashion to execute a mission. This implies that the mission is performed better with both systems employed rather than with just one. It implies that a certain synergy exists between the system&-4hat a different and better effect can be achieved with both systems working together. It also implies that the systems do not conflict with one another, and that employing and engaging both systems does not degrade the effectiveness of one system or, if it does, that the net effect is still positive. The fundamental question addressed in this chapter is how well will the ABL and SBL work together, and whether they have compatible operational strategies. The overall operational strategy includes the deployment, employment, engagement, sustainment, and self-protection as well as the command and control necessary to orchestrate these together into effective laser weapon systems.[29]

The operation of the ABL or SBL on an independent basis will represent a unique challenge for future military commanders. The time sensitivities that are inherent with opportunities for destroying targets, which will exist for a matter of seconds, will demand fast and highly complex information systems and decision making processes. If we assume that both the ABL and SBL become fully operational, military commanders must be able to efficiently and effectively integrate these weapons into a larger system for theater ballistic missile defense. But a combined operational strategy can be devised only if these operational strategies are compatible.

Concepts of operations are uniquely shaped by the operational command, and the extent to which the command influences the operational strategy for any weapon system is determined by that command's experience in war, its understanding of Air Force doctrine, and its ability to anticipate the nature of future conflicts. For revolutionary new weapon systems like the ABL and SBL, it is understandable that the operational strategies lack relevant combat experience. For these reasons, the operational concept for the ABL, as reflected in documents from the Air Combat Command, and the SBL which was written by the Air Force Space Command, involve radically different perspectives on the conduct of military operations. The next section, which presents an independent perspective on the compatibility of A.BL and SBL operational strategy, is derived from two sources: the concept of operation for each system, and an understanding of the technological design and capabilities of the ABL and SBL.

The overall operational strategy for the ABL and SBL is described in terms of missions, command and control, deployment, employment, engagement, sustainment, and self-protection. More relevant terms for SBL (alert, ready) are discussed in the general terms of deployment, employment, and engagement.

Missions

The Airborne Laser and the Space Based Laser programs have both primary and secondary missions.[30] Secondary missions are generally referred to as "potential" missions because these often require modifications to the baseline designs that have not been approved as of this writing.

Furthermore, both program offices are cautious about advertising capabilities that are not currently authorized or funded.

The primary mission of the ABL is theater ballistic missile defense, while the SBL advertises that its two primary missions are ballistic missile defense and counterspace operations. Ballistic missile defense includes both national and theater missile defense. SB12s broader mission of national missile defense (NMD) is to intercept "strategic" missiles in their boost phase, a concept that does not comply with the Anti Ballistic Missile (ABM) treaty. Counterspace missions involve assuring access to space, guaranteeing freedom of operations within the space medium, protecting space assets from attack, and denying the use of space to an adversary. Examples of counterspace missions are those that deny, disrupt, degrade or destroy systems in earth orbit, all of which are classic anti-satellite (ASAT) missions. These missions, however, are considered belligerent and represent a threat to the belief that space is a sanctuary for peaceful purposes. The fact that counterspace missions are politically untenable in the 1990s pushes the ABL and SBL toward the same primary mission of TBM defense.

The fact that both the ABL and SBL share the same mission of theater ballistic missile defense should serve to maximize the ability of devising compatible operational strategies for the two systems. If the SBL should ever be authorized for use in the broader missions of NMD and counterspace operations,[31] then the ABL and SBL will be less compatible in theater operations given the complexities associated with the introduction of competing SBL missions.[32]

The ABL concept of operations includes the secondary missions of cruise missile defense, protection of high value airborne assets, suppression of enemy air defenses, and imaging surveillance. The SBL concept of operations includes the secondary missions of ground surveillance and reconnaissance, tactical designation, hyper-spectral imagery, wind sensing, space object tracking, space object identification, precision employment against terrestrial targets, and nonmilitary missions, such as astronomical data collection and environmental monitoring. While it appears that the SBL has a broader array of secondary missions, in technological terms there is no practical mission performed by the SBL that the ABL cannot also perform. Any differences in the performance of one system are likely to be based on the cost and availability of a weapon system or the political concerns and preferences imposed by policy-makers.[33]

Command and Control

The area that will most likely stress the compatibility between the operational strategies of the ABL and SBL will be in command and control. Command and control includes both the authority to deploy, employ, engage, and sustain each system in theater, and the means to execute that authority (organizationally, individually, and automatically). Engaging either the ABL or SBL against theater ballistic missiles will involve a complex command and control process that blends automated decision-making with human operators through a ground, sea, air, and space-based communications network that defines situation-specific and time-dependent rules of engagement.

ABL will be a dedicated theater missile defense asset for the Joint Forces Commander (JFC) and the Joint Forces Air Component Commander (JFACC). The SBL, by contrast, probably will be "available" to the theater commanders as long as tactical control (TACON) is delegated to the jFACC.[34] The fact that SBL has broader primary and secondary missions may preclude more straightforward command relationships.

Similar to other high value airborne assets, such as the Airborne Warning and Control System (AWACS), Joint Surveillance, Targeting, and Reconnaissance System (JSTARS), and Rivet Joint, the ABL will be assigned to the JFC and controlled by the JFACC. Since the ABL is physically tied to the theater and its primary and potential secondary missions are theater specific, the ABL can remain under the JFC command for the duration of the threat posed by theater ballistic missiles. The JFACC determines the employment configuration for the ABL (continuous and/or overlapping coverage) and controls the ABL through the ABL battle management system. Real-time control of the engagement details for the ABL is delegated to the mission controller who is a member of the ABL crew.

SBL does not require employment direction from the JFACC as does the ABL, nor will it be assigned to theater commanders as in the case of the ABL. According to U.S. law, USCINCSPACE has combatant command (COCOM) over space forces in support of the other Unified CINCs.[35] Consequently, "USCINCSPACE will likely retain combatant command of the SBL system at all times and may delegate operational control to the Commander Air Forces in Space (COMAFSPACE)."[36] In his role as a supporting CINC to the other theater CINCS, USCINCSPACE "may allow Theater CINCs to exercise tactical control in support of assigned missions' "[37] A reasonable assumption is that there will be conflicts over these levels of control for the SBL when military commanders attempt to combine the operational strategies of the ABL and SBL.

The ABL and SBL programs will each have sophisticated battle management systems for fusing multiple data sources and types and incorporating both automated and human positive control. As there is no current motive to integrate the ABL and SBL battle management systems, or even to simplify integration in the future, each program has focused, and will continue to focus, on its own requirements. For example, the SBL incorporates a more centralized command and control architecture than the ABL, for two reasons. First, as mentioned earlier, SBL's weapon's release authority resides at a higher level than does ABL's. Second, as a space-based asset, SBL relies on a centralized and primarily space-based communications network. In other words, any major degradation in our ability to communicate with either the SBL constellation directly or through other space communications assets will have catastrophic effects for SBL command and control. ABL, on the other hand, is not as reliant on space-based communications and thus can operate in a degraded space communications environment because it has a more localized command and control structure.

Deployment

Deployment is the process of moving the asset to the vicinity of the battle so that the weapon system is ready for employment on the battlefield. Because ABL will be based in the continental United States, each aircraft requires a certain amount of transit time to theater, which is estimated to be on the order of 24 hours. SBL, on the other hand, has the benefit of constant presence over any battlefield once it has achieved the full constellation of satellites, with the exception of the extreme polar reaches.[38]

With a constellation of seven ABL platforms, five will be available for deployment at any time, while the other two are expected to be down for inspections, maintenance, modifications, or repairs. The required number of ABLS, which is nominally estimated at two aircraft, will arrive in the theater of operations in a fully combat-ready state within 24 hours of deployment orders. Final pre-firing calibrations, alignments, and system checkouts will Rely occur while the A.BL is enroute to the theater. Airlift or other transportation assets will deploy ABL support equipment and weapon consumables after the initial deployment of the first A-BL .[39]

Employment

Employment means positioning the asset within striking range of its target so that it is ready to engage. In the case of the AEL, employment means positioning the aircraft near the forward line of operating troops, which is within range of potential theater ballistic missiles. As with other high value airborne assets, the ABL must strike a balance between being as close as possible to potential targets to ensure effectiveness, while remaining as far away as necessary to increase its survival against threats to local air superiority. Self-protection capabilities will be discussed in a separate section later in this chapter.

The typical ABL theater employment will include two combat air patrols (CAPS) with a single ABL protected by each CAP. The use of either continuous or overlapping coverage will be determined by the JFACC on the basis of theater geography and the nature of the threat. More than two ABLs can be employed independently inside additional CAPs or within existing CAPs in cooperation with other ABLs to increase theater coverage, conserve the laser fuel on individual aircraft, and increase the capability against multiple theater ballistic missile launches. Voice and data links will transfer target track information between ABLs on orbit and provide the necessary connectivity to the larger battle management system.

As an airborne platform, ABL enjoys the inherent mobility of an aircraft. The orbits of the protective CAP for the ABL will be moved around within the theater based on a variety of factors such as threat locations, threat density, degree of air superiority attained, and other requirements that are determined by the JFACC. Other ABL aircraft will be on alert and will be capable of rapidly replacing or augmenting the ABLs that are being employed.

Once employed and operating within CAP orbits, it may be necessary for each ABL to perform additional calibrations, including assessments of local atmospheric turbulence. While this provision is not included in the current concept of operation, the ABL program has not demonstrated laser lethality at engagement altitudes anywhere, even under test conditions. It is prudent at this point to include turbulence calibrations within employment strategies.

As with deployment, SBUs ubiquitous presence permits simpler employment strategies. Regardless of the density or geographic distribution of missile threats in the theater of operations, the SB12s ability to cover any theater is fixed because it is determined by the geometry of the orbit and the lethal range of the SBL laser. In this study, it is assumed that the SBL constellation is complete, that it is able to achieve the fullest extent of global coverage, and that the SBL is always deployed and employed to any and every potential theater of interest. The SBL, however, also has a fixed capability to respond to theater ballistic missile threats because, unlike ABL, SBUs capability, determined by the number of satellites in its constellation, cannot be easily augmented to increase coverage.

Engagement

Engagement means the actual process of detecting, acquiring, tracking, and killing missiles. Though similar in a broad sense, some differences exist in how the Air Combat Command and the Air Force Space Command envision the engagement of the ABL and SBL, respectively. Each ABL will be equipped with an autonomous infrared sensor suite that provides 360 degree coverage. This suite will be able to detect missile launches and provide immediate trajectory data during the missile's boost phase. Recognizing the atmospheric and weather limitations of this infrared approach, several ABL program documents have mentioned the possibility of augmenting missile detection with active or passive radar. The ABL concept of operations describes interactions with off-board surveillance systems as part of the ABL battle management system, but suggests that this will be used only to assist in target identification and prioritization, rather than detection. ABUs connectivity with essential theater communications systems leaves open the possibility of receiving target detection data from other surveillance assets on the ground, sea, air, or space. For the purposes of this study, the following scenario describes a typical ABL engagement that takes less than 10 seconds.

While on orbit, one or more ABL infrared detection sensors observe a missile exhaust plume. Sensor output and fire control software generate the target's inertial coordinates for the overall theater battle management system, while at the same time providing target location data to the ABL nose-mounted turret control system. Target inertial coordinates are important to the overall theater battle management system because this offers advanced warning to terminal phase systems (of which the Patriot 3 and Theater High Altitude Area Defense are prominent examples) in the event that the missile is not destroyed. Once the appropriate turret telescope in the ABL captures the missile in its field-of-view, the fire control software initiates the course track process. If the turret cannot be moved to see the missile because the missile may lie outside the turret's field-of-motion, then the ABL aircraft will be quickly repositioned or the target data will be handed-off to another ABL that is in a better position in the theater.

Once the target is captured inside the field-of-view of the turret/beam expander, the tracking software begins to conduct passive coarse track with an infrared carnera.[40] When the missile plume is stabilized within the coarse track camera field-of-view, fire control software algorithms estimate the location of the missile body with respect to the plume.[41] After the location and orientation of the missile body are estimated, the internal optical train is pointed ahead of the plume to the missile body and a low power visible laser is fired. This laser floods the missile in order to "paint it visible" against the invisible background of the atmosphere. Some photons reflect off the missile body, return through the ABL beam expander, and make their way back through the optical path into the active fine tracking cameras of the ABL. At this point, infrared missile tracking is still being conducted on the plume, but the fire control system is waiting for the final criteria to be 'met in order to "handover" the track from the plume to the missile body. Once the missile's image is captured within the active fine tracker and is sufficiently stabilized, the final criteria is met and plume-to-hardbody handover occurs.[42] At this point the missile is being tracked in the visible spectrum from photons reflecting from the missile hardbody. The next task is to determine the exact location on the missile body to point the high energy laser. This process may involve applying a standard offset or the more complex task of using a stored data for re-determined offsets based upon the identification of the target.

The next step, atmospheric compensation for the high energy laser, is perhaps the most crucial for the ABL. Atmospheric compensation is a three-step process. First, the atmospheric distortion to a low power laser is measured as that laser is shot through a path in the atmosphere to a point on the missile body that lies ahead of the aimpoint for the high energy laser. Second, the system estimates the degree to which the atmosphere will distort the high energy laser when it is fired only milliseconds later through that same path to the aimpoint. Third, a correcting distortion is applied onto the high-energy laser before it exits the beam expander. This entire process is referred to as "return-wave sensing and correction."

The first step in this process occurs after the target aimpoint has been determined. A low power laser fires through a path in the atmosphere to a "lead-ahead" position on the missile body, which lies ahead of the HEL aimpoint. It is this path through the atmosphere that is measured for the amount of distortion it will cause for the HEL. The "lead-ahead" position is sufficiently ahead of the HEL aimpoint to ensure that when the HEL fires, the measured path from ABL turret to the lead-ahead point on the missile body is the same path through which the HEL will fire to hit the aimpoint on the missile. The path through the atmosphere from the ABL turret to this lead-ahead point will be the same path taken by the HEL.

Once the distortion to the low power laser has been measured, computer algorithms estimate how much the high-energy laser will be distorted as it fires through that same path. Once computed, this distortion (phase and tilt) is applied to the high-energy laser with deformable and fast-steering mirrors. In theory, this process results in a high-energy laser spot that is properly restored and sufficiently lethal to crack or rupture the missile body and thus lead to the catastrophic disintegration of the missile.

The SBL engagement process is similar, with several notable differences. The first difference has to do with detection. Whereas ABL is designed for autonomous detection, the SBL is designed to receive detection information from a host of other intelligence, surveillance, and reconnaissance assets. Also, unlike the ABL aircraft that remains relatively stationary in or near the theater, any given SBL satellite will be over the theater for approximately 19-20 minutes.[43] In other words, a given SBL satellite will offer coverage, either as a sensor or shooter platform, for a given theater for 19-20 minutes during each 112-minute orbit, which is only 18 percent of its orbital period. While one or more SBL satellites within the constellation may be. covering the same theater, it is possible that one SBL may detect a missile launch just before it exits the theater coverage and hand this information over to another SBL satellite. As discussed in the employment section, the fact that theater conditions may not allow overlapping coverage reinforces how important broader interconnectivity is to the SBL, including other communications and intelligence assets in space.

The second difference is that the SBL does not have to perform atmospheric compensation because the laser never traverses far into the atmosphere, if at all. Most of the fire control process-acquiring (detecting) the target, establishing coarse track on the missile plume, predicting the location of the missile body, flooding that body with low power visible photons, stabilizing the hardbody image within the fine track camera's field-of-view, handing over track from passive coarse to active, fine track, establishing fine track on those visible photons, and determining a high energy laser aimpoint on the missile body-is essentially identical to that of the ABL. The critical difference is that the next step in compensating the laser to account for wavefront distortions is not based on anticipated distortions due to the atmosphere, but due to imperfections in the optical resonator within the laser device itself. As such, the SBL "beam clean-up" process occurs by sampling portions of the high-energy laser as it leaves the beam expander. As with the ABL, correcting distortions for the laser are accomplished with deformable and fast-steering mirrors. ABL has a similar source of high-energy laser distortions that it takes into account in its atmospheric compensation process. The fact that SBL does not perform retum-wave sensing and correction, like ABL, leads some to argue that the effectiveness of the SBL is subject to less risk. Some SBL critics argue that atmospheric compensation may indeed be necessary for the SBL and the absence of it will be the technical Achilles heel of the SBL.

Sustainment

Once deployed and employed, both the Airborne and Space Based Laser systems will need to be sustained. Both the ABL and SBL have sustainment strategies for three activities: refueling, rotating crews, and maintaining the aircraft and laser system in good working order. Self-defense can be considered a sustainment activity, but is discussed separately.

Some sustainment activities only occur if the platform has been recently engaged, of which refueling the laser is an example. Other sustainment activities must occur regardless of engagement activity, as with crew rotations. While sustainment activities are common to the ABL and SBL, sustainment strategies and how that activity is accomplished are different. Moreover, for ABL, all sustainment strategies are performed by humans in the theater, while for SBL some of these activities are performed autonomously on orbit.

As an aircraft, ABL is both easier and more difficult to sustain for theater operations. An aircraft can be accessed much more readily than a satellite, which implies that because it is easier to access, the ABL will involve less autonomy in sustainment and demand that more tasks are performed by people. In-theater sustainment implies that additional activities must be planned, coordinated, and executed, and it must be understood that those activities may conflict with employment and engagement.

For both ABL and SBL, the aerospace vehicle and the laser device must be refueled and crew members rotated. The ABL aircraft can be refueled in-flight but the need to rotate crews limits the available time on-station for any one ABL aircraft to less than 24 hours. The aircraft must, however, return to base in order to replenish the laser fuels. The SBL, on the other hand, has no on-board crew members. Ground station crew members will need to be rotated, but this can occur without complicating the employment or engagement strategies of the SBL. However, there are no simple means for refueling either the SBL satellite spacecraft (attitude control thrusters, spent batteries, cryogenics for cooled sensors, etc.) or the laser device. While it is possible to use a manned or unmanned spacecraft to perform a refueling rendezvous during the portion or the SBL orbit that the satellite is not engaged (92 minutes or 82 percent of its orbit), that technology will not be available for the relatively distant future. But refueling the aircraft, the laser device, and rotating crews must be integrated into the overall employment strategy of the weapon. The sustainment strategies that involve maintenance activities, including calibration, trouble-shooting, replacing faulty parts or equipment, differ profoundly between the ABL and SBL given the different degrees of autonomy for each system.

By design, the ABL is less autonomous than SBL. Autonomy is expensive to achieve and simply not as important for the ABL as it is for the SBL. The fact that the ABL has less autonomy means that it will require more frequent maintenance. For example, calibrating some ABL sensors will likely be accomplished on the ground because it is more convenient. For SBL, the same kind of calibrations must be accomplished using more complicated and expensive self-calibration hardware and software sub-systems that are indigenous to the SBL satellite. As a consequence, ABL's sustainment strategies are broader and more complex than those of the SBL.

Self-Protection

The fact that both the ABL and SBL will operate in hostile environments means that each incorporates self-protection measures into the overall employment strategy. As with other high-value airborne assets, the ABL must be able to survive hostile aircraft and surface-to-air missile threats. Threats to SBL satellites could come from anti-satellite or directed energy attacks as well as more subtle forms of interference with the command, control, and communications networks that are on the ground and in space. The ABL and SBL are investigating the possibility of using their high-energy lasers for self-defense. The ABL and SBL will get threat information from their own self-defense suites, an assortment of sensors and countermeasure devices, as well as from AWACS, Rivet Joint, and other air, space, sea, or ground based information systems. Because threats to space assets are not as developed as threats to airborne assets, the ABL has the more challenging task of self-protection, which means that self-protection is more likely to interfere with the primary mission of the ABL.

Summary Assessment

There are major differences in the overall operational strategies between the ABL and SBL. First, the fact that the SBL has missions that are broader than theater missile defense means that theater commanders may be precluded from having complete control over the SBL. Second, the centralized command and control authority of the SBL may complicate or otherwise delay the decision-making process that is necessary to make the SBL available to theater commanders. Given the broader utility of the SBL to the National Command Authority, it is conceivable that the SBL will be withheld from theater commanders at inopportune times. Third, the total time required for deploying, employing, and engaging the ABL and SBL differs greatly. Depending on the theater of operation, the ABL could take up to 24 hours to deploy, while the time required for the SBL to engage satellites could involve as little time as that required to activate the firing process and perform pre-fire system checks-possibly on the order of minutes.[44] Fourth, weather or other atmospheric conditions may degrade the effectiveness of the ABL, while weather has minimal if any effects on the performance of the SBL. Fifth, the ABL can be sustained in the theater on a far simpler basis than is the case for the SBL. Finally, threats to their survivability appear to be more serious for the ABL than the SBL, at least until potential enemies have developed credible anti-satellite capabilities.

VI. Implications

One conclusion of this study is that the Overall compatibility among most of the ABL and SBL technologies is low, but there can be a degree of high compatibility in the operational strategies. This premise leads to certain observations regarding the relationship between the A.BL and SBL as well as the optimal development strategies for both programs.

The first argument, that the ABL is a necessary technological stepping stone to the SBL, or that the ABL and SBL programs have "synergy," simply is not supported by a review of the ABL and SBL technologies. With few exceptions, the technologies employed are incompatible because only a small number of the technologies that are considered significant for the ABL are relevant to the SBL, and vice versa. Furthermore, the experience gained in developing the unique A-BL technologies will have little value for the SBL program, and vice versa. One only needs to examine the history of each program's technology development to understand how minimal is the overlap between the two weapon systems. The near exclusive and non-overlapping nature of the technical risks and challenges for each program strengthens this conclusion.

While the term "stepping stone" may be accurate in a political or psychological sense, it is not accurate in a technological sense. For the reasons noted in this study, the ABL and SBL currently have little technological synergy, although there clearly are areas for potential interaction between the two programs. On the other hand, given the high degree of compatibility in operational strategies and the nature of the ABL and SBL strengths and weaknesses, the potential exist for great operational synergy. These implications lead to two insights regarding the optimal development strategies for the ABL and SBL.

First, despite the relatively low degree of compatibility between the major technologies in the ABL and SBL programs, each system employs some common technologies that are revolutionary, high risk, and have never been integrated or demonstrated on the scales proposed. The fact is that both programs will minimize overall risk if they can maximize the degree of interaction. Given that both programs are well underway, and that the development of the ABL is further advanced than the SBL, it may be necessary to take management and organizational steps to ensure that both programs interact frequently and purposefully.

Second, both the ABL and SBL manifest certain operational weaknesses that could be exploited by enemies if the two systems do not operate together as a "dual system." This option would offer true operational synergy and greater military effectiveness.

Frequent Purposeful Interaction

Independent of a reorganization under one program office, and despite relatively low compatibility between many of the laser system technologies, both programs will acknowledge the need for interaction and yet claim that the nature and frequency of their interaction are sufficient. Both programs are under tremendous political pressure to deliver, but must interact on a regular basis, in spite of these pressures, for two reasons.

The first is that by meeting frequently both the ABL and SBL programs will maximize whatever leverage can exist from each other's programs. Leveraging technologies will reduce the risk for each and increase the level of synergy between the programs. Both will benefit from frequent interaction and cooperation as they develop, integrate, and test technologies, especially in the major technology areas of beam control as well as acquisition, tracking, pointing' and fire control that involve medium to high compatibility.

Even technology areas that showed low compatibility may include "pieces" of technology that are similar or identical between the ABL and SBL. Two examples include the plastic nozzles that are used in both the ABL and SBL laser devices and the command and control software used in the battle management systems. That cooperation is necessary to ensure that the ABL and SBL do not duplicate development efforts or the mistakes that occur when the same contractor is building, testing, and integrating particular technologies for both programs, which is the case with the laser device nozzles. However, defense contractors also suffer from internal inefficiencies, which may preclude the ABL team from consulting with the SBL team (or vice versa) even though they may work in the same facility. Interaction that leverages technologies and uses the experiences of one program to reduce risk for the other program must be encouraged by program leadership and the senior leadership in the US Air Force, the Department of Defense, and the Congress.

Second, frequent interaction might even spur a re-design in the SBL Readiness Demonstrator or the final SBL weapon system based upon the successes or failures that are experienced by the ABL program.

Dual Airborne Laser/Space Based Laser Weapon System

This study has highlighted several strengths and weaknesses of both the ABL and the SBL systems. Interestingly, the strengths and weaknesses tend to be complimentary, which implies that their operational strategies are highly compatible and that there may be prospects for significant operational synergy. The Airborne Laser's strengths lie in the fact that it is closer to the target, has a localized command and control structure, and involves relatively simple repairs, modifications, and refueling for the weapon. By contrast, the weaknesses of the ABL are its sensitivity to atmospheric conditions, including weather, the complexities of theater self-protection, and that, rather than enjoying continual presence, it takes a finite amount of time to get to the theater.

The Space Based Laser's strengths lie predominantly in its ubiquitous nature, ability to operate "above" the weather, vastly simpler task of self-protection, and the fact that it is naturally integrated into other space-based intelligence, surveillance, and reconnaissance assets. On the other hand, the SBL involves a far more complicated command and control environment for global missions, which may limit the availability to theater military commanders at inopportune times. Refueling is also a weakness for SBL in that the technology required for refueling either the spacecraft or the laser modules while it is on orbit do not currently exist. For the same reason, we currently do not have the technologies to perform the modifications, repairs, and upgrades that will be necessary to sustain an SBL constellation.

One conclusion is that the weaknesses of each system may be too pronounced to justify operating alone. But when these weapon systems are combined, the strengths of the ABL tend to compensate for the weaknesses of the SBL, and vice versa. For example, the ABL has the advantage of being closer to the target than the Space Based Laser, although that advantage is somewhat mitigated by the atmospheric turbulence through which the ABL must fire its high-energy laser. In addition, ABL operations will be restricted by other weather conditions, but none of these limitations apply to the SBL. Moreover, the fact that the ABL is in the theater means that it will enjoy localized command and control under the JFACC, while the SBL will have to operate with a more complicated command and control arrangement. While localized control may be seen as a strength, it may in fact be a weakness because the ABL will be another high value airborne asset that the JFACC must manage. With no other conflicting requirements, the JFACC can also control the SBL, however the global capabilities of the SBL suggest that USCINCSPACE will maintain ultimate control of the SBL constellation. But this global contingency may be an overly complicated command and control situation for a JFACC to manage.

In general, the ABL will be more difficult to defend than SBL, at least until anti-satellite technology is as common as threats to airborne assets. The ABL requires at least a degree of air superiority for its safe operation, while the SBL can operate even if the enemy has full command of the air. Not only will the ABL require air superiority, but fighter protection will have to be assigned to all ABL aircraft to ensure their survival.

At the onset of political turmoil, potential enemies will know that the United States has SBLs on orbit that are ready to shoot down ballistic missiles. In the mean time, the ABL can be deployed to the theater to supplement the SBL, which will help to preserve its fuel and operational capabilities for other contingencies.

The ABL and SBL can work in concert to defeat ballistic missiles in the boost phase. As highly lethal, long-range laser weapons, both represent revolutionary new systems which the Air Force has yet to integrate in a synergistic fashion. While individual Air Force commands have articulated how they might use the individual weapon systems, there are no systematic efforts to understand how to meld these two weapons into a unified operational concept.

The principal issue is to build an integrated battle management system for both weapon systems. The current approach is to design battle management systems for both the ABL and SBL on an independent basis, and to integrate these systems when it is necessary to do so. While this may not represent the optimal approach, such cautionary strategies are not Rely to strengthen the viability of either the ABL or SBL, and may in fact communicate a lack of commitment within the defense establishment to these weapon systems.

The lack of an integrated battle management concept is not the only issue to plague the development of an effective operational missile defense system with the ABL and SBL. The fact that the SBL shoots toward the earth while the ABL shoots toward space raises questions about whether stray radiation from the SBL might be captured by the acquisition sensor or main aperture of the ABL. The effects of this condition are unknown, but are of critical importance in the event that both the ABL and SBL lasers might be necessary on occasion to increase the probability of kill against a missile. Such an event raises concerns about the development of automated fire control algorithms that are designed to maximize the ability to engage in cooperative attacks. These and other questions highlight the potential for interference between the ABL and SBL unless steps are taken early in the programs to maximize the value of both weapons in an integrated system for missile defense.

VII. Conclusions and Recommendations

The Airborne Laser and Space Based Laser represent, by all accounts, truly revolutionary weapon systems. Both systems are designed to negate ballistic missiles and will be able to perform a variety of other collateral missions. Both rely on high energy lasers to destroy ballistic missiles in their boost phases, which is possible only with weapons that operate at the speed of light.

While both weapon systems employ high-energy lasers to accomplish a common mission, the technologies employed by each are generally dissimilar. For various reasons, the Airborne Laser cannot be considered a technological stepping stone to the development of the Space Based Laser. The technological heritage of both programs is primarily derived from forces that are internal to these technology development programs, and as such tend to involve relatively little technological leverage from one another. Thus, from a technological standpoint, the development of the Airborne Laser does not enhance the development of the Space Based Laser.

The operational strategies for these weapon systems demonstrate that military commanders will employ the ABL and SBL in significantly different ways. But these differences are a function principally of the inherent strengths and weaknesses of each weapon system, and reflect the different operational environments within which each system will operate. From a strategic point of view, the strengths and weaknesses of the Airborne Laser and Space Based Laser tend to compliment one another, and reinforce the political and technological decision to develop a system for missile defense that employs both the ABL and the SBL. Once understood as the components of a dual system for missile defense, the Airborne Laser and Space Based Laser can provide a capability that neither weapon can provide by itself.

Recommendations

This study draws two broad recommendations for the development of the ABL and the SBL: 1) frequent purposeful interaction; and 2) reorienting toward a dual Airborne Laser/Space Based Laser weapon system.

The first is that both programs will benefit from frequent and purposeful forms of interaction. This coordination can be achieved in various forms to achieve the necessary degree of interaction, including the decision to leave such interaction at the discretion of the directors of the system program offices (SPO). In that case, each SPO Director would have the latitude to ensure the proper frequency and level of interaction, which is consistent with the current method of operation in the ABL and SBL programs. An alternative approach would be to establish a method for oversight by a third party whose function would be to ensure the proper degree of interaction between the ABL and SBL programs. Yet another alternative would be to establish a single laser weapon system program office that would combine the Airborne Laser and Space Based Laser programs under a single Laser Weapon SPO. Such an arrangement would establish a closer degree of interaction between the two technology programs.

At present, the ABL and SBL program offices operate under the auspices of the Air Force Material Command (AFMC) Space and Missile Center (SMC). The ABL program office is located at Kirtland AFB in Albuquerque, New Mexico, while the SBL program office is located at Los Angeles AFB, CA. For this reason, the SMC would be the best organization to oversee the development of both programs. While this is essentially the case today, there could be an over-arching integrated product team (IPT) that operates at the product division level, and which consists of members of the ABL and SBL system program offices, along with representatives from various Air Force Commands, including ACC, AFSPACECOM, SMC, and AFMC. A team with this broad membership would bring the proper mix of expertise for ensuring the development of both the ABL and SBL, particularly in the area of battle management. However, it is questionable whether an IPT like this could maintain sufficient cohesiveness or authority to be effective.

It can be argued that placing both programs under that same reporting authority is the most effective way to ensure that both systems will be designed for optimal operational performance. A single Ballistic Missile Defense Laser System SPO that was comprised of both the ABL and SBL program offices could achieve this objective. One option would be to collocate the program offices, and while this would be the optimal approach it may not be critical to the overall success of the program. The critical feature of this reorganization would be to give oversight and accountability directly to the director of this program office, which with centralized authority and regular reviews could focus on the technologies of mutual interest and the overall battle management system.

The decision to reorient these programs into a dual system represents a major shift in the development philosophies of the ABL and SBL. The implication of this approach is that the Airborne Laser and Space Based Laser become two elements of a larger system for missile defense. While having one program office for the development of laser weapons would be convenient in an organizational sense, the real advantage of a dual system office is to produce greater coordination in' the development of the ABL and SBL, and thus produce a more effective system for defending the United States and its allies against an attack with ballistic missiles.

Glossary

AAA Alignment Annulus Assembly
ABL Airborne Laser
ABM Anti-Ballistic Missile
ACC Air Combat Command
AFMC Air Force Materiel Command
AFSCN Air Force Satellite Control Network
AFSPACECOM Air Force Space Commnand
ALL Airborne Laser Laboratory
AOA Airborne Optical Adjunct
ATP/FC Acquisition, Tracking, Pointing, and Fire Control
ARTS Alignment Reference Transfer System
ASAT Anti-Satellite
ASC Aeronautical Systems Center
AWACS Airborne Warning and Control System
BHP Bipartate Hydrogen Peroxide
BMC4I Battle Management, Command, Control, Computers, Communications, and Intelligence
BMDO Ballistic Missile Defense Organization
CAP Combat Air Patrol
CARD Cost Analysis Requirements Document
CINC Commander In Chief
COCOM Combatant Command
COIL Chemical Oxygen Iodine Laser
COMAFSPACE Commander Air Force Space
CONOPS Concept of Operations
CPCM Common Path Common Mode
DARPA Defense Advanced Research Programs Agency
DoD Department of Defense
FOC Fully Operational Capable
HABE High Altitude Balloon Experiment
HEL High Energy Laser
HF High Frequency
HF Hydrogen Fluoride
HVAA High Value Airborne Asset
ICBM Intercontinental Ballistic Missile
IFF Identification Friend or Foe
IPSRU Inertial Pseudo Star Reference Unit
IPT Integrated Product Team
ISR Intelligence, Surveillance, Reconnaissance
JFACC Joint Forces Air Component Commander
JFC Joint Forces Commander
JSTARS Joint Surveillance Tracking and Reconnaissance System
LAMP Large Advanced Mirror Program

LODE	Large Optics Demonstration Experiment
NBC	Nuclear, Biological, Chemical
NCA	National Command Authority
NMD	National Missile Defense
SAS	Stability Augmentation System
SGLS	Space Ground Link System
SBIR	Space Based Infrared Radar
SBL	Space Based Laser
SDIO	Strategic Defense Initiative Organization
SMC	Space and Missile Systems Center
SPO	System Program Office
TACON	Tactical Control
TBM	Theater Ballistic Missile
TDRSS	Tracking and Data Relay Satellite System
TMD	Theater Missile Defense
UHF	Ultra High Frequency
USAF	United States Air Force
USCINCSPACE	U.S. Commander in Chief Space
VHF	Very High Frequency

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Notes

1. Unlike the ABL program which is to deliver seven laser weapon systems, the current SBL program is to deliver only an orbiting laser lethality demonstrator, called the Space Based Laser Readiness Demonstrator. The 1972 Anti-Ballistic Missile treaty is currently interpreted to prohibit basing anti-ballistic missile weapons in space.

2. ABL's primary mission is theater ballistic missile defense. SBL advertises two primary missions: ballistic missile defense and counterspace. Ballistic missile defense includes both national and theater missile defense. SBL's broader National Missile Defense (NMD) mission is boost phase intercept of strategic missiles, which does not comply with the current ABM treaty. Counterspace missions involve assuring access to space, guaranteeing freedom of operations within the space medium, protecting space assets from attack, and denying an adversary's use of space. Examples of counterspace missions are those that deny, disrupt, degrade or destroy systems in earth orbit-classic anti-satellite (ASAT) missions. These missions, however, are considered belligerent by nature and compromising to the notion that space is a sanctuary for peaceful purposes. Counterspace missions are, therefore, politically untenable. Consequently, in the author's opinion, both ABL and SBL are currently moving forward with the same primary mission: TBM defense.

3. Airborne Laser (ABL) System Cost Analysis Requirements Description, unclassified version 2.1 (Boeing), 19 August 96, 8.

4. Concept of Operations for the Space-Based Laser (SBL) Systen4 Air Force Space Command, 15 December 1997, Draft.

5. Theodore A. Postol, "Lessons of the Gulf War Experience with Patriot," International Security, Winter 1991/92, pp. 1 19-17 1.

6. New World VISTAS, Air and Space Power for the 21st Century, Directed Energy Volume (W6shington D.C., United States Air Force Scientific Advisory Board, 1995), 2.

7. Ibid.,22.

8. A pop-up toaster and toaster oven both use similar heating elements with similar temperature control electronics. Only the overall size and orientation differ, necessary to support the different size and orientation of their unique subjects (slices of bread versus frozen dinners). Interestingly, a toaster oven can perform the same mission as the pop-up toaster for a slice of bread, albeit less efficiently.

9. The 1947 collapse of the Tacoma Narrows Bridge is a good example of scaling mistakes. The original bridge design (probably demonstrated in a scaled-down model) did not account for the physical effects of high winds that sometimes flow through the Narrows Gorge. The engineering design called for a length/width dimension that created a very sensitive structural mode at an unfortunately low frequency, a frequency that could be generated by high winds. The bridge in fact

collapsed as high winds excited the bridge at its resonant frequency because the design was not scalable.

10. An example of this would bean investment by Project A in Project B's construction of a new test facility. Project A does not need to own the test facility, only use it. A small investment gains access to the facility without having to pay for one in its entirety. In this way, Project A has wisely leveraged Project B's test capability.

11. A deformable mirror, sometimes referred to as a rubber mirror, is a mirror with a pliable surface that allows electromechanical actuators to push and pull on its surface, creating various deformations. Deformable mirrors are used within adaptive optics systems to eliminate wavefront errors from incoming images or outgoing high energy lasers.

12. Some will argue that the SBL program has not settled on the hydrogen flouride technology for the SBL laser device and that deuterium flouride technology is still an option. While this is true, the SBL program is currently using hydrogen flouride technology in its Readiness Demonstrator design and hydrogen flouride technology will be used as a point of reference for the SBL weapon system in this paper.

13. "[The optical resonator] uses a waxicon/reflaxicon beam compactor set and a powered, retro-reflecting rear cone to extract laser energy from the annular gain medium and compact the large annular beam into a 25cm diameter circular beam." See Space Based Laser Technical Description Document, Lockheed Martin Astronautics, Denver, Colorado,
January 20, 1997, 1-7 1.

14. Though the Space Based Laser Technical Description Document states the primary mirror will be 8m diameter, on-going studies suggest this may be too small.

15. The fact that the SBL plans to use a higher wavelength HEL than the ABL makes SBL's task of grinding the primary mirror surface somewhat less difficult; achieving the same RMS (Root Mean Squared) surface smoothness specification for a lower wavelength laser is harder than for a higher wavelength laser. However, achieving the kinds of RMS specifications required for laser weapon applications on large optics (8-12m diameter) poses the most serious fabrication challenges. The effects of gravity sag on the large substrate block and on grinding tools are two such challenges. Fabricating large optics in smaller segments is a reasonable work-around but does mitigate serious challenges in assembly while maintaining integrated surface smoothness.

16. The BMDO-funded, Phillips laboratory-executed Structural Pointing Integrated Control Experiment (SPICE) (an SBL technology development program) achieved some success in active and passive damping technology on a truss structure of similar size.

17. The difference between separate and shared aperture systems has to do with incoming versus outgoing lines-of-sight. A.BL is "predominantly" a shared aperture system because it uses the main aperture to accomplish most beam control and ATP/FC functions. The exception with ABL is that it uses a separate, small aperture acquisition camera to acquire and coarse track the missile plume. The most notable consequence of ABL's shared aperture design is its common path common mode

(CPCM) active fine track function, enabled in part by its aperture sharing element. SBL, on the other hand, separates beam control and ATP/FC functions more clearly in that SBL performs active fine track through its two meter separate ATP aperture.

18. A wavefront sensor segments a cross-section of the laser beam into small patches, called subapertures using an array of lenslets. The lenslet array focuses the laser light from each subaperture onto small sections of a high frame rate focal plane array. 'Me wavefront the center of that tilt in each subaperture is the amount the focused spot displaces away from small section of the sensor.

19. A wavefront reconstructor takes data from the wavefront sensors, performs a large matrix multiplication to compute wavefront tilt for each subaperture, and combines those tilts together to reconstruct, or estimate, the wavefront of the full aperture. It then computes the opposite, or conjugate, wavefront which it uses to drive the deformable mirror. The deformable mirror takes on the conjugate wavefront which cancels out the original wavefront error.

20. On the SBL, the high energy laser's path to target does not pass through the severe phase distorting portions of the atmosphere as does AB12s high energy laser.

21. ABL's acquisition sensor is located inside the nose-mounted turret and sees the target through a separate window. ABL is referred to as a shared aperture system because the HEL, low-power illuminator lasers, coarse plume tracker, and active fine tracker all share the main aperture. Only the wide field-of-view acquisition sensor looks through a separate aperture.

22. Passive track is performed using reflected photons from the target illuminated only by the sun or other natural occurring phenomena. Active track is performed using reflected photons generated by an illuminating system, such as a laser.

23.'Me SBL design includes four separate apertures. As with ABL, SBL incorporates sensors mounted outside the vehicle (on the spacecraft) designed to detect TBM launches. SBL refers to these as acquisition sensors. The apertures supporting these sensors are not counted among SB12s four apertures. SBL's first aperture supports the passive coarse (plume-infrared) tracker, the second aperture (2m) supports both the passive intermediate (plume-infrared) tracker and the active fine (hardbody-visible) tracker. The second aperture also transmits the laser ranger. The third aperture is used to transmit the illuminator laser. The fourth aperture is the 8m main aperture and is used to transmit the HEL beam.

24. The SGLS transceiver provides communication between the SBL satellites and the Air Force Satellite Command Network ground stations and receives commands, transmits telemetry, and provides a frequency for ground tracking. SGLS technologies include transponders, high data rate transmitters, and multi-directional antennas.

25. For reference, TDRSS communications is used to provide relay communication when SBL satellites do not have line-of-sight visibility directly to a ground station and as an alternate path for communications to the ground.

26. The SBL laser cross-link coordinates an integrated battle management between each SBL satellite in the constellation. The laser communications transceiver terminal is used for SBL spacecraft-to-spacecraft communications within the constellation providing necessary data rates to communicate real time battle information between satellites in different orbital planes. Laser communications technology includes redundant transmit telescopes with laser diodes as optical sources for the data stream. Co-aligned with these transmit telescopes is a small receiver telescope which focuses the incoming optical data stream onto a photodiode for detection. A separate aligned laser diode beacon assists in acquiring, pointing, and tracking these telescopes. 'Me entire optical assembly is mounted on a 3-axis gimbal assembly to permit acquisition, pointing, and tracking of other satellites.

27. See William H. Possel, Lasers and Missile Defense: New Concepts for Space-Based and Ground-Based Laser Weapons (Montgomery, AL: Occasional Paper No. 5, Center for Strategy and Technology, Air War College, July 1998); Thomas D. Bell, Weaponization of Space: Understanding Strategic and Technological Inevitabilities (Montgomery, AL: Occasional Paper No. 6, Center for Strategy and Technology, Air War College, January 1999).

28. This level of detail is not found in the SBL technical descriptions.

29. See Mark E. Rogers, Lasers in Space: Technological Options for Enhancing US Military Capabilities (Montgomery, AL: Occasional Paper No. 2, Center for Strategy and Technology, Air War College, November 1997), for an analysis of the military functions that can be performed by lasers.

30. Secondary missions are referred to as adjunct missions in ABL documentation and ancillary missions in SBL documentation.

31. Some believe that SBL will never be built or deployed if the National Missile Defense mission is not authorized.

32. The two systems become less compatible because SBL will not be completely available for theater use. Battle management will likely become more complicated in this scenario.

33. The author does not mean to insinuate that range to target is not a definite discriminator between ABL and SBL. 'Mere are certainly scenarios where ABL simply cannot engage a target because it is outside the ABL's lethal range.

34. Tactical control includes control of the asset for a particular battle. It does not include control of the asset outside the theater or for any purposes other than direct theater support.

35. Title 10, U.S. Code, Section 164

36. Draft Concept of Operations for the Space Based Laser (SBL) Systen4 December 15, 1997, 14.

37. Draft Concept of Operations for the Space Based Laser (SBL) Systen4 December 15,1997,14.

38. The inclination of the SBL orbits will limit its lethal ground footprint to latitudes between 750 N and 750 S. Establishing a constellation of twenty SBL satellites is not a trivial task. Estimates of $60B to $IOOB and twenty-plus years exist. Current heavy spacelift capability does not exist.

39. Weapon consumables may be prepositioned in theater.

40. In this context, "passive" implies that track is established on a plume signature; "coarse" implies the largest tracking field-of-view with lowest degree of tracking stabilization.

41. Up to this point, the missile plume is being tracked in the infrared; the missile body is not visible in the infrared.

42. Plume-to-hardbody handover is the process of transfering control of all active beam train elements (fast steering mirrors and inertial reference platform), including the turret/beam expander, from the passive infrared coarse plume tracker to the active visible fine hardbody tracker.

43. This is based upon an orbit altitude of 13OOkm (orbit velocity of 7.2 knvsec), a maximum SBL range of 40OOkm, and a theater extending 500-10OOkm.

44. It is too early in the SBL system design to know how much pre-filing preparation can or will be done on a routine basis on-orbit.

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