



**NAVAL
POSTGRADUATE
SCHOOL**

MONTEREY, CALIFORNIA

THESIS

**LIDAR DESIGN FOR SPACE SITUATIONAL
AWARENESS**

by

David Gast

September 2008

Thesis Advisor:

Co-Advisor:

Brij Agrawal

Dan Boger

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 2008	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE: LIDAR Design for Space Situational Awareness			5. FUNDING NUMBERS
6. AUTHOR Gast, David W.			8. PERFORMING ORGANIZATION REPORT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			10. SPONSORING/MONITORING AGENCY REPORT NUMBER
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE
13. ABSTRACT (maximum 200 words) Space Situational Awareness (SSA) is a growing concern for National Security. Among the many methods of increasing SSA is the use of space-based Laser Imaging, Detection And Ranging (LIDAR) sensors to detect, track, classify or image other spacecraft. This Thesis explores the unique trade-spaces and design decisions faced by an engineer designing such a system. It provides an overview of the basic operational principles, the major components, the impact of one design choice on all other decisions, and guidelines for making design choices when designing a space based LIDAR for Space Situational Awareness applications. System operational constraints, demands on the host spacecraft, and potential impacts on other spacecraft are explored. Finally, an illustrative system design is presented, demonstrating the interaction between system requirements, system design, and component selection.			
14. SUBJECT TERMS LIDAR, Laser Radar, LADAR, Space Situational Awareness, Satellite Payload Design, Active Optical Sensors, Satellite Detection and Tracking			15. NUMBER OF PAGES 97
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

LIDAR DESIGN FOR SPACE SITUATIONAL AWARENESS

David W. Gast
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1996

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ASTRONAUTICAL ENGINEERING

from the

**NAVAL POSTGRADUATE SCHOOL
September 2008**

Author: David W. Gast

Approved by: Brij N. Agrawal
Thesis Advisor

Dan C. Boger
Co-Advisor

Knox Millsaps
Chairman, Department of Mechanical & Astronautical Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Space Situational Awareness (SSA) is a growing concern for National Security. Among the many methods of increasing SSA is the use of space-based Laser Imaging, Detection And Ranging (LIDAR) sensors to detect, track, classify or image other spacecraft. This Thesis explores the unique trade-spaces and design decisions faced by an engineer designing such a system. It provides an overview of the basic operational principles, the major components, the impact of one design choice on all other decisions, and guidelines for making design choices when designing a space based LIDAR for Space Situational Awareness applications. System operational constraints, demands on the host spacecraft, and potential impacts on other spacecraft are explored. Finally, an illustrative system design is presented, demonstrating the interaction between system requirements, system design, and component selection.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	MOTIVATION	1
B.	OBJECTIVE	3
C.	DEVELOPING REQUIREMENTS.....	4
D.	OUTLINE	5
II.	BASIC LIDAR OPERATION	7
A.	SYSTEM OVERVIEW	7
1.	Basic LIDAR.....	7
2.	Adding Complexity	8
B.	GOVERNING EQUATIONS AND COMPONENT INTERACTIONS ...	8
III.	TYPES OF LASERS AND WAVELENGTH CONSIDERATIONS.....	11
A.	ADVANTAGES OF LASERS	11
1.	Monochromaticity.....	11
2.	Directionality	12
3.	Brightness	13
B.	HOW LASERS WORK.....	13
1.	Pumping	13
2.	Population Inversion.....	14
3.	Resonant Cavity	15
C.	TYPES OF LASERS.....	16
1.	Solid State	16
2.	Liquid.....	18
3.	Gas.....	18
4.	Chemical	19
5.	Diode.....	19
6.	Free-Electron.....	20
7.	Summary.....	21
D.	WAVELENGTH CONSIDERATIONS.....	22
1.	Detectability.....	22
2.	Interference	24
3.	Target Reflectivity	24
E.	LASER SELECTION.....	24
IV.	TELESCOPE DESIGN	27
A.	TELESCOPE DIAMETER.....	27
B.	TELESCOPE FOCAL LENGTH	27
C.	TELESCOPE DESIGN	28
D.	TRANSMIT OPTICS	31
E.	OPTICAL TRAIN LOSSES	32
V.	DETECTOR ALTERNATIVES.....	33

A.	LAYOUT ALTERNATIVES.....	33
1.	Single Pixel.....	33
2.	Multiple Pixel	35
3.	Advantages and Disadvantages	35
4.	Exotic Implementations.....	37
B.	TECHNOLOGY ALTERNATIVES.....	39
C.	WAVELENGTH CONSIDERATIONS.....	41
1.	Materials	42
2.	Filters	43
D.	PHOTOMULTIPLIERS AND IMAGE INTENSIFIERS	45
E.	SUMMARY	46
VI.	POINTING AND SLEWING REQUIREMENTS.....	47
A.	SCANNING METHODS.....	47
1.	Raster Scan	47
2.	Spiral Scan.....	49
3.	Planar Scan.....	50
4.	Random Scan.....	51
B.	KNOWLEDGE VS. CONTROL	51
C.	ATTITUDE AND POINTING.....	53
VII.	SOURCES OF NOISE.....	55
A.	INTERNAL SOURCES.....	55
1.	Laser.....	55
2.	Electronic Noise.....	56
a.	<i>Thermal Noise</i>	56
b.	<i>Dark Noise</i>	56
c.	<i>Quantization Noise</i>	58
d.	<i>Signal Processing Noise</i>	58
B.	EXTERNAL SOURCES	58
1.	In the Field of View.....	58
2.	Off-Axis Sources.....	60
VIII.	SYSTEM INTERACTIONS	63
A.	POWER REQUIREMENTS.....	63
1.	Always On.....	63
2.	Predicted On.....	63
3.	Unpredictable and Intermittent.....	64
B.	THERMAL REQUIREMENTS	65
1.	Always On.....	65
2.	Predicted On, Unpredictable and Intermittent.....	65
C.	PROCESSING REQUIREMENTS.....	66
IX.	POTENTIAL IMPACT ON OTHER SPACECRAFT	67
A.	THERMAL EFFECTS.....	67
B.	FOCAL PLANE DAMAGE.....	68
C.	CROSSLINK INTERFERENCE	69

X.	DESIGN EXAMPLE	71
A.	OVERVIEW.....	71
B.	MISSION REQUIREMENTS	71
C.	LASER SELECTION.....	72
D.	TELESCOPE DESIGN	73
E.	FOCAL PLANE DESIGN.....	75
F.	SENSOR OPERATION	76
G.	TECHNICAL CHALLENGES.....	77
	WORKS CITED.....	79
	INITIAL DISTRIBUTION LIST	81

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

Figure 1.	EM Transmissivity in Atmosphere (From: Olsen 66)	2
Figure 2.	CALIPSO	4
Figure 3.	Laser Emission vs. Spontaneous Emission (From: O’Shea 165)	12
Figure 4.	Two Level Pumping	14
Figure 5.	Multi-Level Pumping (From: O’Shea 98)	15
Figure 6.	Solid State Laser	17
Figure 7.	Diode Pumped Solid State Laser	20
Figure 8.	Free Electron Laser	21
Figure 9.	Newtonian Telescope.....	28
Figure 10.	Gregorian Telescope.....	29
Figure 11.	Nasmyth Telescope.....	29
Figure 12.	Cassegrain.....	29
Figure 13.	Schmidt Cassegrain.....	30
Figure 14.	Effect of Spherical Aberration on a Point Source.....	31
Figure 15.	Pixel FOV > Laser FOV	33
Figure 16.	Laser FOV > Pixel FOV	34
Figure 17.	Detector response curves (After: Raytheon Vision Systems IR Wall Chart, 2006)	43
Figure 18.	Photomultiplier Diagram	45
Figure 19.	Raster Scan.....	48
Figure 20.	Raster Scan, Unconstrained in Elevation.....	48
Figure 21.	Raster Scan, Unconstrained in Azimuth	49
Figure 22.	Spiral Scan	50
Figure 23.	Planar Scan.....	51
Figure 24.	Dark Noise Current (After: Raytheon Vision Systems IR Wall Chart, 2006)	57
Figure 25.	Typical Nd-YAG Laser Head	73
Figure 26.	Lightweight Telescope by Shafer Corporation.....	74
Figure 27.	Detail of CMOS-APS array	75
Figure 28.	LIDAR System Layout	78

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

This thesis would not have been possible without the initial interest and faith of Professor Dan Boger, or the inspiration of Professor Brij Agrawal. It could not have been developed without LCDR Andy Presby, and it would never have been completed without Michelle Sullivan.

I would like to acknowledge my parents for loving and shaping me, my friends for putting up with me, my fiancé for loving me and making me better, and, above all, God, for creating this wonderful world, redeeming it, and placing me in it.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. MOTIVATION

Space Situational Awareness (SSA) is vital to the United States of America. More than any other country, the U.S. utilizes space for military command and control, military and civilian navigation, communications, intelligence, and a host of other applications (Rumsfeld 9). Knowing what is orbiting our planet and the orbits in which those objects are located is essential to maintaining those capabilities.

To date, most efforts in detecting, tracking and cataloging objects in orbit have been carried out by earthborn means. Radar emplacements like The Fence track every object of sufficient size that passes overhead, then update the catalogues in a more or less automated fashion. Other radar and optical sites can track orbiting objects as they pass within their fields of view, and some can even locate objects as far out as the GEO belt.

Unfortunately, each of these methods requires the object to be tracked to pass overhead. Any object in an orbit that does not do so cannot be tracked. For instance, The Fence cannot track anything in an inclination *low enough not to cross it*. Furthermore, most of these methods require a tracked object to be correlated to a launch in order to identify the object. Any significant maneuver while out of sight of a ground station could easily generate an uncorrelated track.

The limitations of earthborn sensors grow out of three facts. First, any such sensor must be, by definition, on the ground. The highest piece of ground is only 8.85 km above sea level, and is hardly an ideal location for building anything. Most satellites, on the other hand, have a perigee at or above 600 km, due to atmospheric drag considerations. Thus, to be useful, any such sensor must be able to detect objects at least that far away.

Second, the range of orbits visible to any given site is constrained by its physical location. Furthermore, many such sensors require multiple passes before a solid track is developed, and all require periodic revisits to maintain their tracks. Mobile sensors can help to alleviate the first problem, but not the second, since moving them to cover different orbits would cause them to lose track on those objects spotted previously. There

are also practical and political issues with the placement of such systems. A given location may be ideally situated to observe a particular range or orbits, but it may present a challenging environment for constructing and operating such a system. Other locations may be ideal both positionally and environmentally, but may be controlled by someone who would prefer not to have a space observation sensor located there.

Third, and of particular concern for optical systems, though not inconsequential to radars, is the fact that any earthborn system must look up through the atmosphere. The atmosphere distorts, disperses, reflects and absorbs various electromagnetic wavelengths to different degrees.

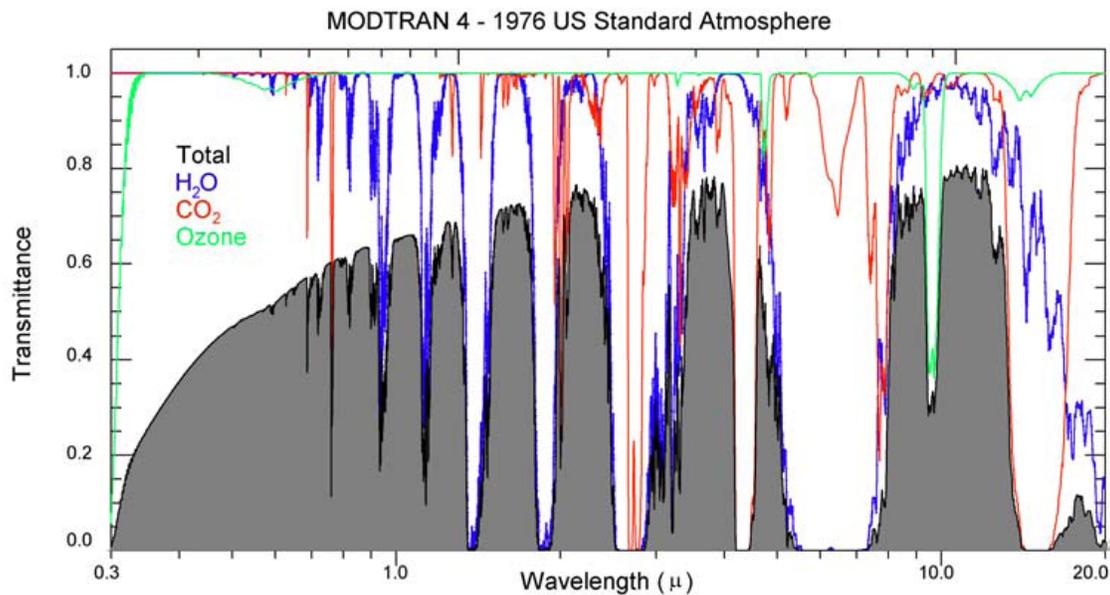


Figure 1. EM Transmissivity in Atmosphere (From: Olsen 66)

As a result of these inherent limitations of earthborn sensors, a great deal of interest has developed in improving Space Situational Awareness through space-based means. Space-based sensors can operate at shorter ranges, allowing lower power requirements for active sensors and better resolution with smaller apertures for both active and passive sensors. These sensors can be launched into almost any orbit without dealing with territorial issues. They do not, in most cases, have to deal with atmospheric effects. They also move very quickly compared to satellites not in similar orbits,

allowing a relatively small constellation of satellites, correctly deployed, to cover every orbit from short-term LEO orbits out to the GEO belt.

The exact nature and composition of such a constellation is outside the scope of this thesis. However, along with more traditional SSA sensors, Laser Imaging, Detection And Ranging devices (LIDARs) could be used to great effect in such a constellation. LIDARs possess the optical resolution and imaging capabilities of passive optical sensors while also providing the range information and independence from light sources of RADAR. Incidentally, depending on whom you ask, LIDAR stands either for LIght Detection And Ranging or LAser Imaging, Detection And Ranging. The same technology is also known as LADAR (LAser Detection and Ranging) and Laser Radar.

B. OBJECTIVE

The goal of this thesis is to analyze and illustrate the system design process for developing a space-based SSA LIDAR. It explores the basic operation of a typical LIDAR system, examines the roles of the primary system components, and takes a system level view of the interactions and tradeoffs between the components.

This thesis is not intended to make the reader an expert in any individual LIDAR component. Many excellent books and papers have been written on lasers, telescopes, photo-detectors and other subsystems that comprise a LIDAR. Several such resources can be found in the bibliography of this thesis. Instead, this thesis is intended to provide a guide to designing a space based LIDAR for SSA applications. It should be useful to anyone developing a LIDAR for any application, but it is focused specifically on the problems and decisions encountered in this specific mission area.

Most space-based LIDARs to date, such as Clementine, GLAS and CALIPSO, have been developed for terrain mapping or aerosol detection. Obviously, such LIDARs must deal with the constraints imposed by being designed for spaceflight, but they are generally nadir-pointing sensors for which the object or substance they are designed to detect fills their field of view. For them, there is no question of searching a large volume for small objects, which can be a wide array of distances away. The one notable

exception to this rule is the RELAVIS system employed by XSS-11, but that system is optimized for proximity operations with satellites in very similar orbits whose general position is well defined.

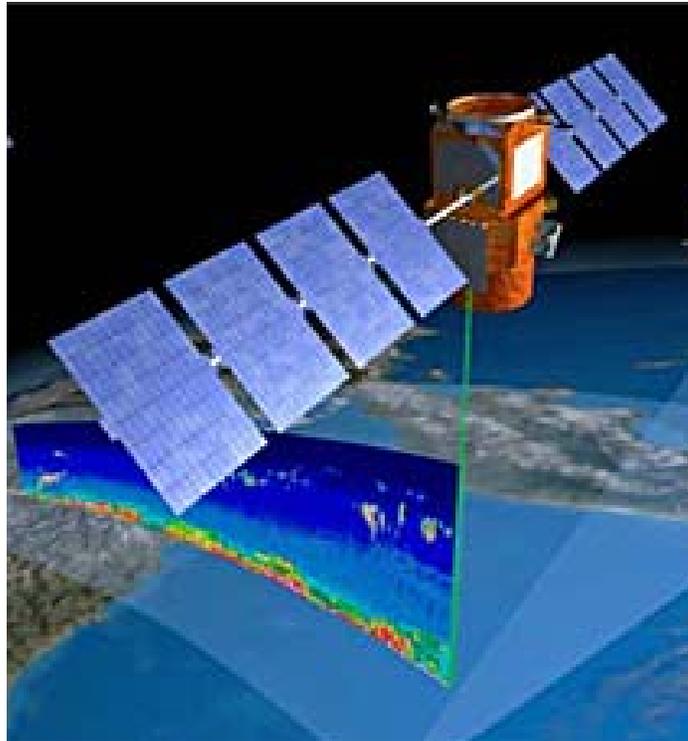


Figure 2. CALIPSO (After: NASA <http://www-calipso.larc.nasa.gov/about/> 8 Feb 08)

LIDARs of the sort contemplated by this thesis are broadly constrained by the mass, size and power restrictions common to all satellite payloads.

C. DEVELOPING REQUIREMENTS

Beyond the scope of this thesis, but vital to the process of designing a LIDAR for Space Situational Awareness, is the problem of developing the requirements for the sensor. Obvious considerations, such as maximum detection range, expected target size, scan rate, search volume, and resolution requirements must be considered. There are other, less obvious requirements that need to be explored as well. Will the sensor be looking only into deep space, or will it have to point towards the earth as well? Will the sensor be on at all times, or only for short periods of time? How frequently will the system be turned on and off? What, if any, countermeasures should the system be able to

handle? What types of relative motion are expected from the objects that will be detected? What is the minimum range at which the system will be required to operate?

If the answers to these questions are not well defined, the rest of the design process cannot proceed. As will be seen in the chapters to follow, critical choices depend on knowing exactly how, where, when, why, and for how long the system will be operating. The exact nature of the targets to be tracked is also crucial. Of course, it is possible to design a system that could successfully track any object from suborbital to super-GEO, of any size, through almost any interference, despite any countermeasures. Unfortunately, such a system would be at least the size of the International Space Station, and would probably cost tens, if not hundreds of billions of dollars.

In short, the better defined the requirements are, the better the sensor will carry out its intended mission with the least amount of mass, power and cost.

D. OUTLINE

This chapter lays out the scope and goals of this thesis. Chapter II provides an introduction to the principles of LIDAR and an overview of the component interactions. Chapters III-V explore the choices available for the three major systems components and the decisions that factor into component selection. Chapters VI and VII explore the effects that this sensor has on the design of the spacecraft in which they are installed. Chapter VIII deals with the effects such a sensor may have on other spacecraft. Chapter IX provides an example of a system designed using the processes outlined in Chapters II-VIII.

THIS PAGE INTENTIONALLY LEFT BLANK

II. BASIC LIDAR OPERATION

This chapter will provide an overview of LIDAR designs, along with a brief discussion of the interactions between the various components that comprise a LIDAR.

A. SYSTEM OVERVIEW

1. Basic LIDAR

The simplest LIDAR design consists of a laser illuminator, a collecting telescope, and a single photo-detector. The laser sends out a pulse along the axis of the telescope. The pulse reflects off of any objects along its path, and the return pulses are focused by the telescope onto the photo-detector. The time at which the pulse is received is compared to the time the pulse was sent, and the range of the object is determined by the range equation:

$$R = \frac{t_r - t_t}{2c} \quad (0.1)$$

Where R is the Range, t_r is time received, t_t is time transmitted, and c is the speed of light in a vacuum.

Such a system is only capable of detecting objects directly along the axis of the sensor. Azimuth and Elevation are determined by the direction in which the sensor is pointing. Any sort of search or scanning must be accomplished by physically pointing the sensor in the direction to be searched.

The resolution of such a sensor is determined, as with all LIDARs, by the interrelationship of the laser-beam width, the resolution of the telescope, and the size of the pixel. Simply put, if the pixel's field of view (FOV) is greater than or equal to the area illuminated by the laser pulse, the pixel will detect anything within the beam, and the resolution is determined by the beam width. If the pixel's FOV is less than the area illuminated by the pulse, only objects within the pixel's FOV will be detected. This improves the system's resolution, but it may mean that the object for which the search is being conducted may be illuminated without being detected. This type of system will be discussed further in Chapter V

2. Adding Complexity

Beyond this simple design, a wide range of options are available to the designer for improving the system's performance:

Scanning mirrors can both direct laser pulses to off axis targets and send returns from off axis targets to fixed detectors, enabling the LIDAR to scan within its field of regard without moving most of the structure of the instrument itself. Beam expanders can be used either to focus a laser beam into a smaller divergence angle or to spread the beam across a wider area. Scanning mirrors and beam expanders will be discussed in Chapter IV.

Multiple pixel detector arrays can allow for resolution within the beam width of the laser and detection of off-axis returns. These detectors, their benefits and drawbacks will be discussed in Chapter V.

The method of illumination itself may be altered in a variety of ways. Rather than relying on a single pulse at a time, a train of pulses may be sent out in a burst, and the returns may be considered together, which can improve the probability of detection and range resolution, but at the cost of slower scans and smaller search areas. Lasers of different frequencies may be used, together or separately, to improve probability of detection against different targets, or to avoid spoofing attempts. Pulse widths and wavelengths may be varied as well, to a variety of different effects. These methods will be discussed in Chapters III and V.

B. GOVERNING EQUATIONS AND COMPONENT INTERACTIONS

The equations involved in designing a LIDAR are surprisingly few and, with one exception, extremely straightforward. The simplest are those dealing with resolution and, consequently, telescope design. First and foremost is the Rayleigh criterion:

$$TSD = 1.22 \frac{\lambda}{D} R \quad (0.2)$$

Where TSD is the Target Separation Distance, λ is the laser wavelength and D is the telescope diameter.

Closely coupled with this is the focal length equation:

$$FL = \frac{PS \cdot R}{TSD} \quad (0.3)$$

Where FL is the focal length and PS is pixel size.

Together, these two equations drive the minimum diameter and focal length requirements on the telescope. The telescope can, and often should, be larger than resolution requirements demand, but it can be no smaller. This will be discussed further in Chapter IV

On the laser side, without going too deeply into laser theory, only the beam divergence angle equation is significant for sizing the laser aperture and determining whether any beam expansion is required:

$$\sin \phi = 2.44 \frac{\lambda}{d} \quad (0.4)$$

Where ϕ is the beam divergence angle, and d is the laser aperture diameter (O'Shea 16).

The most significant and most complex equation, and the one that reflects the interactions between the various components of the system, is the LIDAR range equation

$$N_{pr} = \frac{E_p \sigma \rho \lambda A_{tel}}{hc \pi^2 R^4 \tan^2 \phi} \quad (0.5)$$

Where N_{pr} is the number of photons received by the detector per pulse, E_p is the energy per pulse, σ is the cross sectional area of the target, ρ is the reflectivity of the target, A_{tel} is the area of the telescope aperture, h is Planck's constant, and c is the speed of light (Brownlow 3).

The LIDAR range equation is similar in form to the radar range equation, but varies in a number of significant ways. First, and most importantly, it deals with energy rather than power, since the signal received by the focal plane is in the form of photons. The power per pulse only matters when considering whether a given laser can send the requisite amount of energy in the desired pulse width and whether the transmit optics can handle the flux. Second, the LIDAR equation converts the energy received into units of photons; hence the λ , h and c terms. Third, it uses beam divergence rather than transmit antenna gain, and aperture size rather than receive antenna gain.

There are, of course, other losses, such as transmissivity and reflectivity of mirrors and lenses in the transmit and receive optical chains, imperfect detection on the focal plane, and misalignments, which are not reflected in the equation above for reasons of clarity. These terms will be discussed in Chapters IV and V.

As this equation illustrates, any change in one of the components alters the requirements on each of the others. For instance, a shorter wavelength would either require a larger aperture, a narrower beam, or a higher energy pulse to get the same number of photons back to the detector. A larger aperture, on the other hand, would allow for a lower energy pulse, a wider beam, or a less sensitive detector.

The version of the equation described above is specifically formulated for detecting objects that are smaller than the cross sectional area of the beam. For applications in which the object illuminated is larger than the area illuminated, the equation is simplified to:

$$N_{pr} = \frac{E_p \rho \lambda A_{tel}}{hc\pi R^2 N_{pix}} \quad (0.6)$$

Where N_{pix} is the number of pixels that can “see” the illuminated area.

This form of the equation is used for terrain mapping and many imaging applications, the latter of which may be used for SSA applications.

Again, both equations above ignore several system losses for clarity.

III. TYPES OF LASERS AND WAVELENGTH CONSIDERATIONS

This chapter explores the desirable (and undesirable) characteristics of lasers, the advantages of different types of lasers, and factors to be considered when selecting a laser.

A. ADVANTAGES OF LASERS

The laser is the enabling technology for all LIDAR systems. Its advantages as an illuminator come from several properties inherent and unique to lasers.

1. Monochromaticity

Monochromaticity refers to the spectral purity of laser light. Considered simply as a light source, a laser provides the purest light of a single color that can be produced by man. When considered in the context of a link equation, this allows for very high Signal-to-Noise Ratios (SNR), due to the narrow bandwidth of the signal. Most potential sources of noise, the most significant of which is the sun, produce broadband signals. With sufficiently narrow optical filters, the vast majority of this noise can be ignored. This advantage will be addressed again in Chapter V, and sources of noise in general will be addressed in Chapter VII.

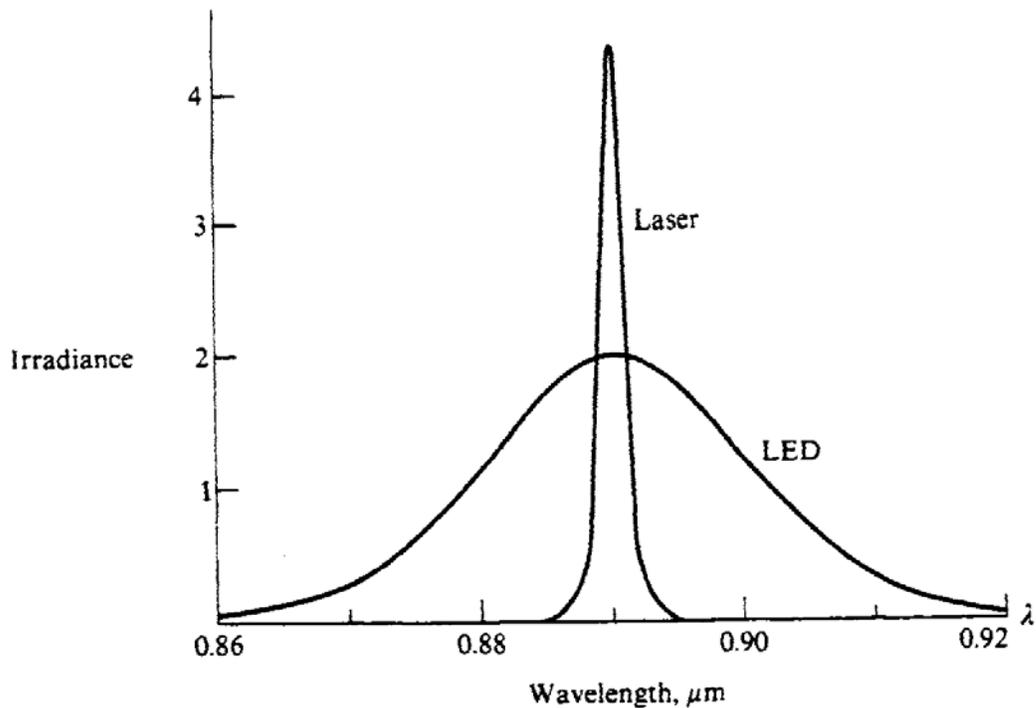


Figure 3. Laser Emission vs. Spontaneous Emission (From: O'Shea 165)

2. Directionality

The laser's chief advantage as an illumination source is its directionality. With the exception of a very few high-gain systems, most lasers employ collimating tubes that reflect the laser energy back and forth many times before allowing it to escape through the aperture. This collimation has the practical effect of producing a nearly planar light wave, rather than the spherical waves produced by most light sources. This nearly planar wave arrangement allows the beam to propagate with spreading confined to the divergence angle, which is defined by the laser-tube geometry and aperture size. Typical beam divergence angles are on the order of one milliradian, though slightly wider and significantly narrower beams can be produced (O'Shea 18, 48).

Ideally, a laser employed for LIDAR illumination should be designed to produce a beam with exactly the desired beam divergence. If this is not possible, however, the angle can be altered by the use of beam expanders, as will be discussed in Chapter IV.

3. Brightness

A laser's brightness is a product of the monochromaticity and directionality of the light it produces. By focusing very spectrally pure light into a very small solid angle, extremely bright light can be produced with very low power. As noted previously, most other light sources spread their energy over a broad spectrum, from ultraviolet well into the infrared bands and, in the case of the sun, beyond. As a result, lasers operating at power levels less than a mW are literally brighter than the sun at their own wavelengths (O'Shea 18, 33).

B. HOW LASERS WORK

Although "laser" is now used generically as an ordinary word, it was, originally, an acronym: Light Amplification by Stimulated Emission of Radiation. This acronym describes not only what a laser does, as most acronyms do, but also how it does it. With the notable exception of the Free-Electron Laser (FEL), all lasers work by increasing the population of high energy molecules and reducing the population of low energy molecules in a lasing medium through a process known as pumping. As the molecules seek to return to their lower energy state, they emit photons at the energy level of the transition through which they are passing. So far, this is almost the same process used for fluorescent tubes. In lasers, however, this process occurs in a collimating tube, which reflects the photons emitted along the laser axis back into the lasing medium. As these photons interact with the high energy state molecules in the medium, they stimulate the emission of more photons along the same axis and at the same energy, which amplifies the light several orders of magnitude beyond the typical spontaneous emissions from the same substance.

1. Pumping

Pumping is the term applied to whatever method is used to produce the desired population inversion. Pumping can be produced by optical means, such as flash lamps or lower-powered lasers; mechanical means, such as forcing gasses through supersonic nozzles; chemical means, harnessing the energy of exothermic reactions; or electrical means, ionizing the laser medium by placing a voltage differential across it (Kuhn 13, 19).

Optically pumped lasers are the easiest type to comprehend, since the significant energy transactions are all between photons and excited atoms. A photon at the pump energy excites an atom, some photons at the laser energy are spontaneously emitted which, themselves, hit other atoms to cause stimulated emission. This is the usual pumping method for solid-state and liquid lasers. The only real difference between this method and the others is the manner in which the excitation is achieved. From that point on, the process is essentially the same.

2. Population Inversion

To induce a substance to lase, it is not sufficient just to increase the number of high energy molecules and decrease the number of low energy molecules. A population inversion must be produced, which means that there must be more high energy molecules than there are low. Without this population inversion, spontaneous emission will occur, but stimulated emission cannot.

The simplest case would be one in which there are only two energy levels to consider: an upper state and a lower. The pumping would raise the molecules to the upper state. Then, stimulated emission would take them back to the lower. Unfortunately, lasing media for which this ideal state of affairs occurs are exceedingly rare (O'Shea 64-65). Instead, most lasers have three or four level transitions, and systems with many more levels are not uncommon. Helium Neon lasers, for example, transition through six levels (Kuhn 280-283).

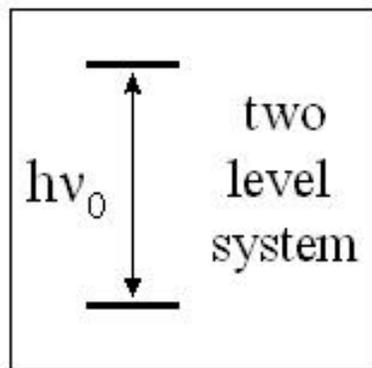


Figure 4. Two Level Pumping
(From: http://www.unc.edu/~dtmoore/laser_intro.html 8 Feb 08)

In a three level system, the molecules are pumped to a high energy state which is easy to pump to, but which transitions to a lower state too quickly to produce a population inversion. The lower state to which it transitions however, is more stable, and does allow for the required inversion. The transition from that state back to the ground state is the laser transition. Four level systems work similarly, only the laser transition is between two intermediate energy levels, involving neither the highest energy state nor the ground state. The energy released in non-laser transitions is generally in the form of heat, and contributes to system inefficiency (O'Shea 127).

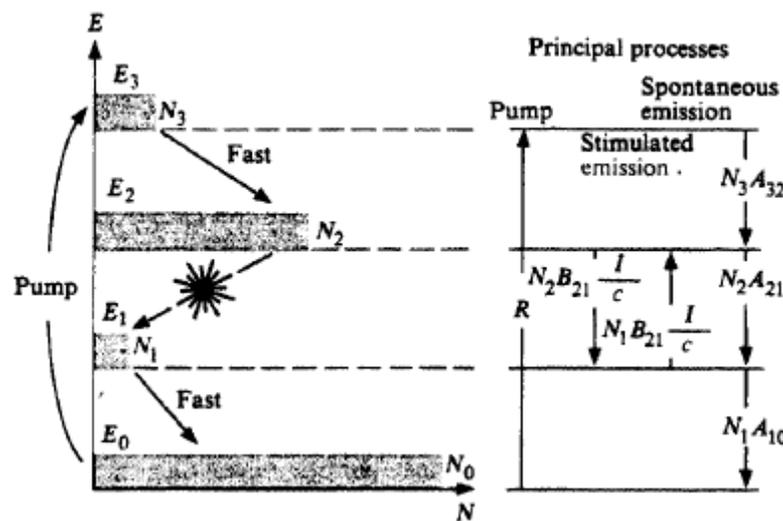


Figure 5. Multi-Level Pumping (From: O'Shea 98)

One common misconception is that the higher energy state referred to above always involves a valence electron jumping to a higher shell. While this is often the case, excitation may also be vibrational or rotational, and the vibrational energy states can involve different modes of vibration (Kuhn 387).

3. Resonant Cavity

There are a few high gain lasers, such as some chemical and gas lasers, capable of producing stimulated emission with just one pass through the laser medium. Most lasers, however, require the beam to be reflected back through the medium multiple times to achieve the desired gain. This resonant cavity has the added benefit of, in effect, increasing the distance between the light source and the aperture. The practical result of

this is that the wave fronts are nearly planar by the time they exit the aperture. The aperture itself bends the waves somewhat as they exit, but it is this collimation that gives the laser its outstanding directionality (O'Shea 73-76).

C. TYPES OF LASERS

1. Solid State

The first laser ever built was a solid state laser. It used a ruby crystal rod as the laser medium, with silvered ends on the rod for collimation, and a helical flash lamp wrapped around it to pump it. Solid state lasers today are found in a wide variety of shapes and sizes, made from different materials capable of a wide range of wavelengths and power levels. While many still use crystals and flash lamps, many other materials and pumping methods are now available.

Glass rods and disks doped with various materials can be shaped more precisely than grown crystals, and some of the most promising technologies for LIDAR applications are fiber lasers: optical fibers doped with lasing materials. Fiber lasers are already in widespread use for communications links. As higher energy fiber lasers are developed, their high efficiency, sometimes surpassing 40%, makes them an attractive option for LIDAR developers.

While flash lamps are still used, many modern solid-state lasers are actually pumped by other lasers. This significantly improves the overall efficiency of the system, since the pumping only occurs at the optimal frequency, rather than the broadband pumping supplied by a flash lamp. Most pump lasers are diode lasers, described below, but a Titanium-Sapphire laser, for instance, may be pumped by a Neodymium Ytterbium Aluminum Garnet (Nd-YAG) laser, which may, itself, be pumped by a diode laser.

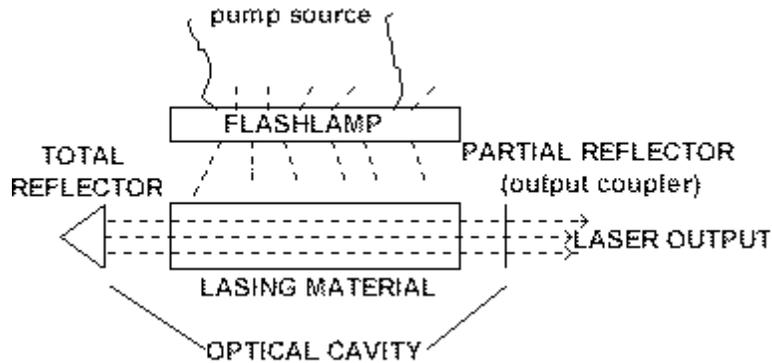


Figure 6. Solid State Laser

(From: <http://web.princeton.edu/sites/ehs/laserguide/index.htm> 8 Feb 08)

Solid-state lasers have the advantage of being able to exist at a wide range of temperatures without damage, though their operating temperature ranges are considerably more narrow. Being solid, they tend to maintain their shape over time. Depending on the material used, they can handle moderately high power levels and conduct heat quite efficiently. Also depending on the material and pumping method, they can be operated in Continuous Wave (CW) or pulse mode.

Because most solid-state lasers use crystals or glass rods as their lasing medium, they are subject to cracking or shattering if too much power is put through them too quickly, or if their temperature changes too rapidly. Obviously, impacts or heavy vibrations can also damage the laser. Fiber lasers are less susceptible to these types of damage. Unfortunately, most fiber lasers manufactured so far are intended for communications use and do not produce the pulse energies needed for long-range LIDAR applications. Should sufficiently powerful fiber lasers be developed, their high efficiency and ruggedness would make them ideal for such missions.

The most common laser used, at present, for LIDARs, and one of the most commonly used solid-state lasers overall, is the Nd-YAG laser. This material is capable of handling relatively high power levels (>1J per pulse), has excellent thermal properties, can attain wall-plug efficiencies better than 10%, and operates at 1064 nm, which, while IR, is still within the detection range of silicon. The importance of this last point will be seen in Chapter V.

2. Liquid

Liquid lasers, often referred to as dye lasers, work on the same principles as solid state lasers. They are optically pumped, and can produce reasonably high pulse energies. Their chief advantage, for our purposes, is that there are dyes which fluoresce at almost any wavelength within the visible band. They also spread their laser energy over much broader bands of wavelengths than do most solid-state lasers. The broader bandwidth, with proper laser design, allows the laser to be tunable within the dye's band, which means the laser's output can be altered to avoid interference from and with other systems. The disadvantage of this is that a great deal of energy is wasted in the energy at undesirable wavelengths, and having a tunable laser makes focal-plane design more difficult, as shall be discussed in Chapter V.

An alternate approach to the broader bands would be to allow the entire spectrum to be transmitted. In a LIDAR system, however, this would require either a wider filter on the focal plane array, which would significantly decrease the signal to noise ratio, or a detector which only detects a portion of the spectrum, which reduces system efficiency.

Another consideration which tends to make liquid lasers less suitable for space-applications are their susceptibility to temperature extremes. Obviously either freezing or boiling would have a significantly deleterious effect on the laser, very possibly rupturing the container in which the liquid is held. Also, many liquid lasers require the lasing medium to be flowing through the laser chamber, which means that piping, reservoirs, and pumps become necessary to operate the system. On the whole, these lasers are not well suited to space-based applications.

3. Gas

Unlike the solid-state and liquid lasers discussed above, gas lasers are generally not pumped optically. Most are pumped electrically, much like a fluorescent light tube, while a few are pumped mechanically. This mechanical pumping, also known as gas-dynamic pumping, is too complex to be desirable for most spacecraft applications, as it involves forcing the lasing medium through a supersonic nozzle in order to achieve a population inversion. In open cycle operation, such a system would limit the lifetime of

the laser to the amount of gas stored on boards and would present problems by thrusting the spacecraft when in operation. Closed cycle systems exist, but they tend to be quite large and require pumps, reservoirs and piping, as with the liquid lasers.

Only two types of gas lasers are sufficiently powerful and well developed to be of interest for LIDAR applications. Carbon Dioxide lasers are extremely powerful, are widely used for industrial purposes and, consequently, are widely available and well understood. Their laser output is around $10\mu\text{m}$, which is well into the IR portion of the spectrum. Sensors operating in this wavelength may be desirable for some applications, but they do require more exotic focal planes, most of which must be cooled to operate.

Excimer lasers are also well developed, and are frequently used for medical applications. Their attractiveness comes from the fact that they operate in the UV region, which means that very small optics can produce extremely good resolution. Unfortunately, like dye lasers, they require flowing gasses to operate.

Both these lasers require very high voltages to operate, and both require exotic focal planes to detect the return signal. Consequently, neither is particularly well suited for most space based LIDAR applications, but, should particular design constraints demand a sensor that operates in the mid-range IR or UV, they might merit consideration.

4. Chemical

The most powerful lasers currently in existence are chemical lasers. They achieve their population inversions through exothermic chemical reactions. Unfortunately, these lasers are almost always open systems, and the products of the reactions are generally caustic. Any time such a laser is operated, it emits a cloud of rather nasty chemicals which, for a space application, could be extremely problematic. While such a laser could be used for a ground based LIDAR system where the laser exhaust and the telescope optics can be geographically separated, chemical lasers are impractical for space-based LIDARs.

5. Diode

Diode lasers are now the most common variety of lasers. CD players, DVD players and laser pointers all use them. They are similar to Light Emitting Diodes in the

same way that gas lasers are similar to fluorescent tubes. Any further explanation would require an extensive discussion of semiconductor theory. Suffice it to say that they are excellent low-power laser sources, but are, by themselves, not sufficiently powerful for LIDAR applications. They do, however, serve extremely well as pump sources for solid state lasers, because they concentrate all of their energy into the ideal wavelength for optically pumping the material to which they are coupled. Using diode lasers instead of flash tubes significantly increases the efficiency of the lasers they pump.

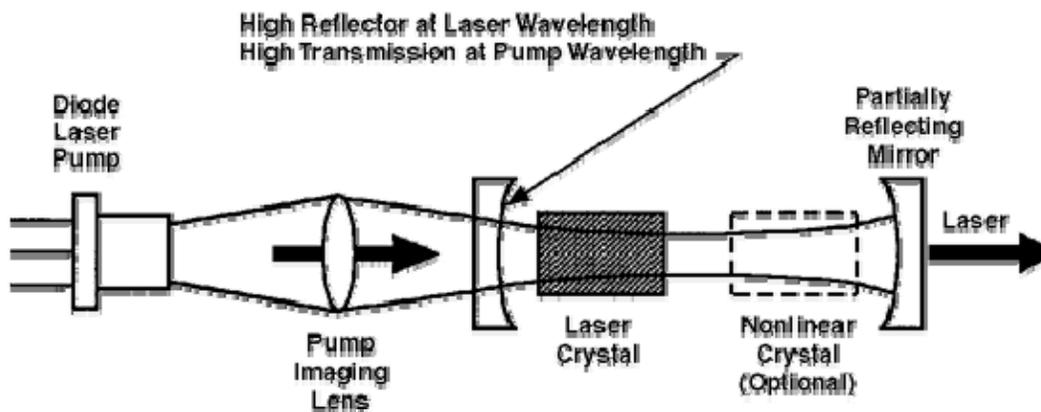


Figure 7. Diode Pumped Solid State Laser (From: http://www.nasa.gov/centers/langley/news/factsheets/LaserTech_prt.htm 8 Feb 08)

6. Free-Electron

Free-Electron Lasers (FEL's) are completely different than any other type of laser. Rather than exciting some sort of lasing medium, as do all of the lasers discussed above, they use a high energy electron beam to produce the photons desired. A beam of high energy electrons is sent through a "wiggler," an alternating magnetic field which causes the electrons to vibrate back and forth. This vibration induces the electrons to emit photons at the "wiggler" frequency. These photons are then collimated, cause stimulated emission from other electrons, and are emitted as a laser beam.

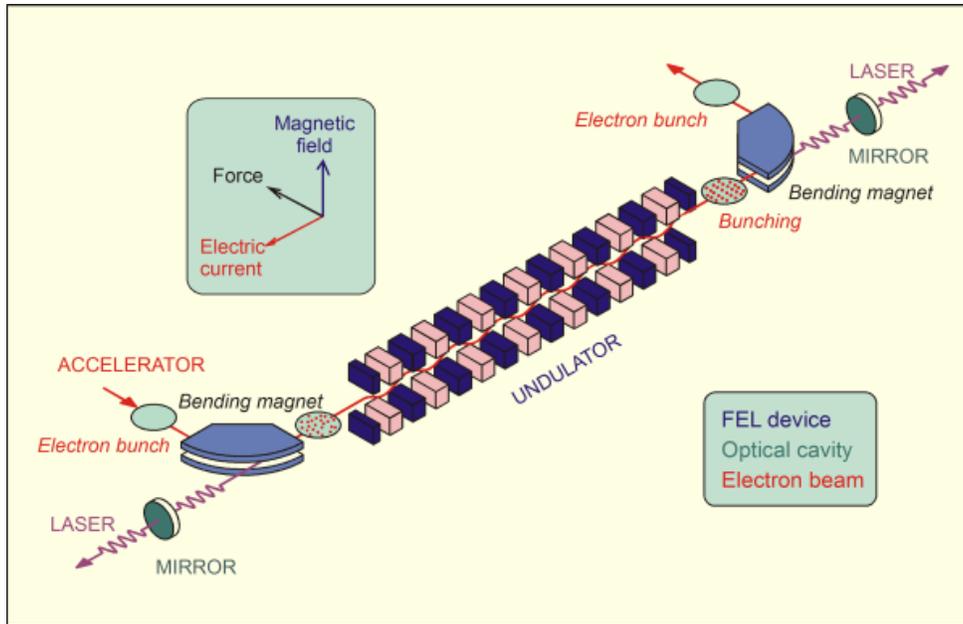


Figure 8. Free Electron Laser (From: <http://wonda.iae.kyoto-u.ac.jp/outline-e.html> 8 Feb 08)

The great advantage of such a laser is that the “wiggler” can operate at essentially any frequency, from IR to UV. They are also theoretically unlimited in the level of power they are capable of emitting. This would seem to make this an ideal choice for any LIDAR system. Unfortunately, FEL’s are still early in their development, so commercial systems will not be available for some time. More significantly, the physics of the electron beams required to operate such a system makes the laser so large, it could only be housed on a satellite the size of a space station. Future developments and breakthroughs may make these lasers practical for space applications some day, but they are currently too big and too new to be considered

7. Summary

While many types of lasers exist, and are useful for a wide variety of applications, the only technologies mature and powerful enough to be used for space-based LIDARs are solid-state lasers and, possibly, carbon dioxide or excimer lasers for very specific applications.

D. WAVELENGTH CONSIDERATIONS

The wavelength at which the system is to operate is the single most significant decision made in the design process. The wavelengths available are restricted to those produced by the lasers under consideration. The type of detector to be used is driven by the wavelength chosen. The optic size and resolution of the system is also determined by this choice. Every aspect of the system design is influenced by this choice.

Each type of lasing medium lases at specific wavelengths. Some media lase at two or three different wavelengths. For these systems, the desired color is generally promoted while the less desirable are suppressed by laser cavity design and the use of filters. Still, the wavelengths available are limited to those produced by lasers capable of producing the energy levels required by the system being designed. It is possible, through the use of frequency doublers or triplers, to shorten the wavelengths. However, these necessarily reduce the overall efficiency of the lasers, and they still only increase the number of frequencies available by a small amount. Still, there are high powered lasers that produce light in wavelengths ranging from IR to UV, so some other criteria must be used. Below are the factors that must be considered when choosing an operating wavelength.

1. Detectability

Detectability encompasses two very different considerations. First, what sort of focal planes are capable of detecting the wavelength chosen? This aspect of the issue will be considered in Chapter V. Second, how overt or covert is the system intended to be? If the design is intended to be completely overt, then this consideration does not matter. If, however, the designer wished to be able to operate this system without other systems being able to detect it, then a wavelength unlikely to be detected must be selected. A variety of considerations must then be contemplated.

The beam of the laser itself can only be detected if it falls onto a detector. Essentially, it must illuminate the detector to be seen. As shall be discussed in Chapter VIII, such illumination should generally be avoided whenever possible in any case. To

accomplish this, however, may take some very sophisticated planning and programming of the sensor, including knowledge of where such detectors are likely to be located at all times.

With concern over the use of lasers as anti-satellite weapons, there is the possibility that many future systems may be equipped with laser detectors, which would then significantly exacerbate the problem of avoiding detection. Since avoiding illumination of any satellite that may be equipped with a laser detection system is highly impractical for a system intended to improve SSA, the only way to avoid detection would be to operate at wavelengths not detected by such systems.

Since, unless there is widespread proliferation of laser detectors on orbit, the beam will generally not be detected, it is the illuminated target that is of concern. Such illumination will be substantial for any application, and should be obvious to any sensor observing the target at the specified wavelength. Two solutions, which may overlap, are possible. The first is to operate at a wavelength not generally detected by sensors which are likely to observe the target. Since most optical systems work in the visible and near infrared regions, lasers deeper into the IR and UV spectra would be useful for this application. There are, of course, optical systems that operate in these regimes, but even they tend to be looking in specific bands. If these bands are avoided, the illumination should remain undetected.

The second, similar method involves only earth-based sensors. Since the preponderance of SSA sensors currently are and are likely to remain earthbound, this should avoid most potential detections. By this method, wavelengths that do not propagate well through the atmosphere are selected, preventing the illumination energy from reaching the target at all.

Since there are a number of wavelengths that are not typically detected which also do not propagate well through the atmosphere, selection of the proper wavelength should be relatively straightforward. Of course, the technologies for detecting those wavelengths can be complex and expensive, often requiring substantial cooling. While the designer may not wish to have the illumination detected by unfriendly sensors, the

return pulse must be detected by the focal plane for the system to work at all, and anything that can be detected by one sensor could be detected by others.

Overall, attempting to make the sensor covert through wavelength selection will likely significantly increase the cost, mass and complexity of the system. The designer should carefully consider the importance of covertness to the mission before committing to designing such a sensor. Use of a passive sensor would be far more covert than any active system, and active sensors can be made covert far more easily through the manner of their employment than through their inherent design characteristics.

2. Interference

The potential impact of a space-based LIDAR on other satellites will be considered in Chapter VIII. The likely future proliferation of lasers in space for communications purposes should be considered here. Unfortunately, the wavelengths of the lasers that will be used in such systems remain undetermined at this point. As such systems become more common, more information will likely be available about them, and the designer will be able to consider this factor more thoroughly.

3. Target Reflectivity

Target reflectivity is usually the most important consideration, if the exact nature of the target or targets is known. Most spacecraft are designed to be highly reflective over a wide spectrum of electromagnetic radiation. This is generally done for thermal control reasons. Thus, for detecting run-of-the-mill spacecraft, almost any wavelength will produce a strong return. If, however, the sensor is designed to detect a specific class of targets, then knowledge of the reflectivity of those targets would be invaluable to the designer. As seen in the LIDAR range equation, the more reflective the target is at the wavelength used, the stronger the return will be, and, consequently, the laser selected can be significantly less powerful, reducing power, thermal, and mass requirements for the system.

E. LASER SELECTION

Because the most significant variables in the LIDAR range equation are Range, which is taken to the fourth power, and divergence angle, which is squared, a first order estimate of the energy per pulse needed by the laser can be determined without selecting

the other components. This estimate will indicate the subset of lasers that are available. Considering the wavelengths produced, efficiencies, complexities and reliabilities of these lasers should narrow the list of available types further. Once this is done, first order decisions regarding the other components can be made based on the few candidate lasers and basic system comparisons can be done. One could, of course, select the focal plane or telescope design first, but the laser selection has the most impact on the overall system design, so it is generally best to begin there.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. TELESCOPE DESIGN

In some ways, the telescope is the most straightforward element of any LIDAR system. Resolution requirements and the laws of physics dictate that an aperture of a minimum size is required. The pixel size on the detector and those same laws of physics require a specific focal length based on the aperture diameter chosen. Unfortunately, this only gives the lower limit to telescope size. The upper limit is based on factors far less easy to determine.

A. TELESCOPE DIAMETER

As noted above, the minimum diameter is determined by the Rayleigh criterion. The maximum is determined by the spacecraft size, the mass allowance or the state-of-the-art in large mirror manufacture. In this dimension, bigger really is better. Essentially, the rule is that you should get the largest diameter telescope you can fit, afford or lift. There are drawbacks to large mirrors: they tend to flex more than smaller mirrors, they are only manufactured by a very few companies, mass increases with the square of the radius, larger telescopes are harder to slew, etc. Still, the designer should select the largest optic that can fit the constraints under which he or she is operating.

The reason for this is light gathering, not resolution. As reflected in the LIDAR equation in Chapter II, the number of photons detected from the target is directly proportional to the area of the telescope aperture. In short-range applications, this does not make much of a difference. For detecting small targets hundreds or thousands of km away, however, a larger aperture could allow detections of smaller objects or farther objects, potentially with lower power lasers or less efficient detectors.

B. TELESCOPE FOCAL LENGTH

As discussed in Chapter II, focal length is a function of telescope diameter, pixel size and resolution requirements. This relationship points out an additional reason to select the largest aperture possible. For a given resolution requirement, the larger the aperture and smaller the pixel, the shorter the focal length can be, which means that the telescope can be more compact in the axial dimension. This is particularly beneficial for

LIDAR designs that require rapid slewing of the telescope, since it reduces the moment of inertia about any slewing axis. It will also have the effect of raising the frequency of most of the telescope's vibrational modes.

C. TELESCOPE DESIGN

The type of telescope selected is generally determined by the mass constraints and the desire to fit the telescope within the smallest space possible. As noted above, the shorter the telescope is, the easier it is to slew. Most space-based LIDAR designs have used reflector type telescopes, since they tend to be lighter than equivalent refractor type telescopes, though refractor telescopes have been used successfully as well. Of the reflector telescopes used, most have been Cassegrain designs, since that design allows the longest focal length to be folded into the smallest overall length compared to the other basic reflector types illustrated in Figures 10-13.

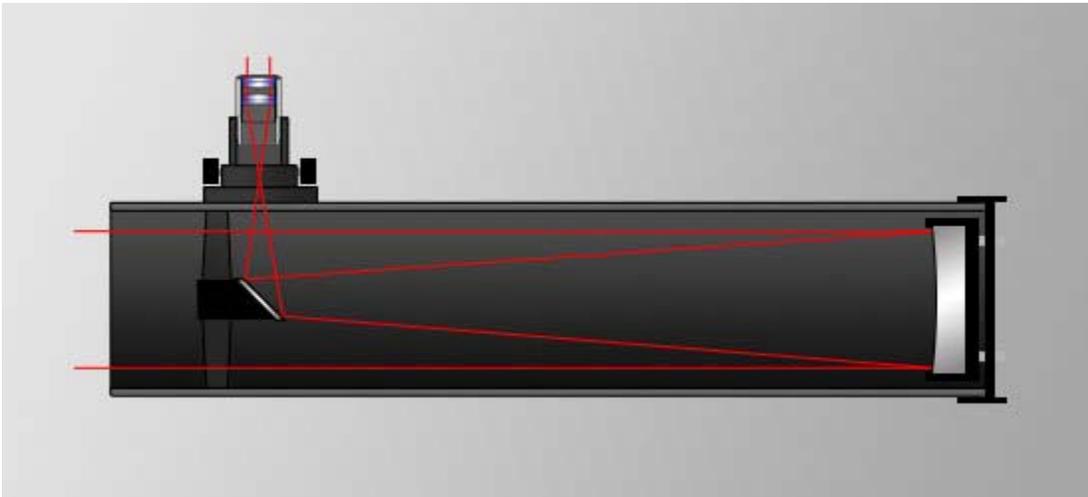


Figure 9. Newtonian Telescope (From: http://starizona.com/acb/basics/equip_telescopes_newtonians.aspx 8 Feb 08)

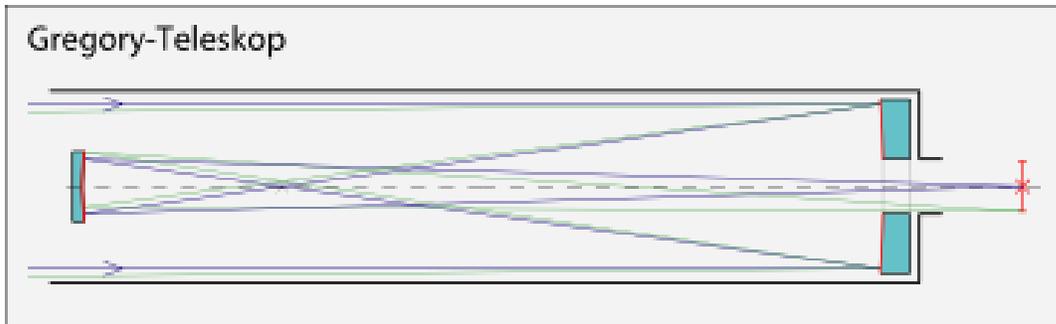


Figure 10. Gregorian Telescope (From: <http://www.answers.com/Gregorian+telescope?cat=technology> 8 Feb 08)

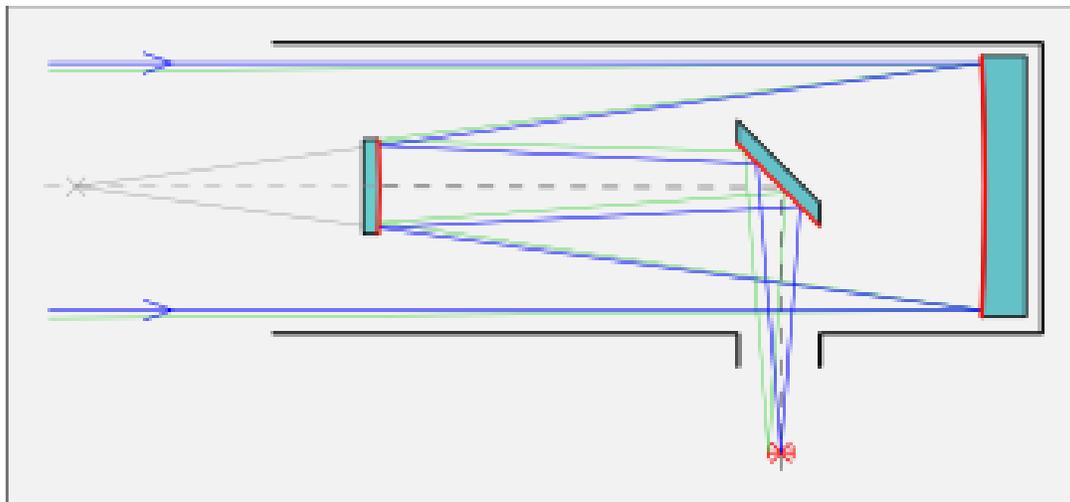


Figure 11. Nasmyth Telescope (From: <http://www.answers.com/topic/nasmyth-telescope> 8 Feb 08)

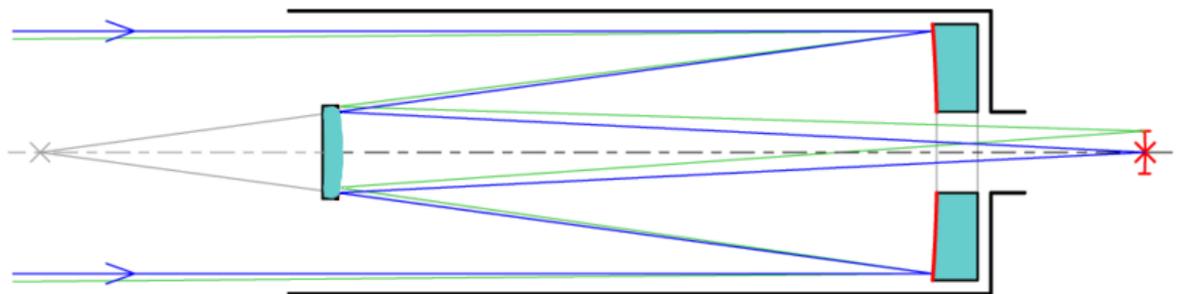


Figure 12. Cassegrain (From: <http://www.answers.com/topic/cassegrain-reflector> 8 Feb 08)

There are more complex telescope arrangements than the types illustrated above which allow for smaller telescopes through further folding of the optical path, unobstructed apertures, optical corrections, wider fields of view, etc. A thorough investigation of these types is beyond the scope of this thesis, but one specialized variant, The Schmidt Cassegrain, may be of interest for some LIDAR applications.

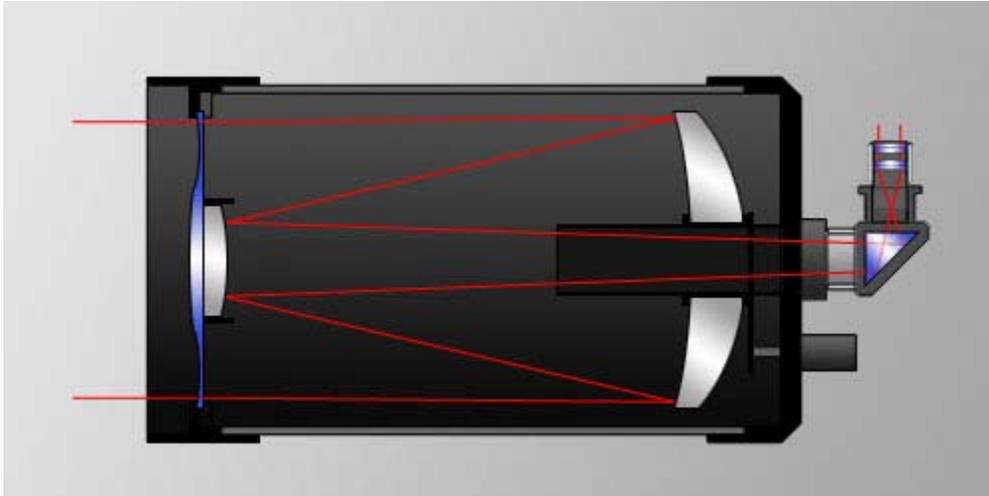


Figure 13. Schmidt Cassegrain (From: http://starizona.com/acb/basics/equip_telescopes_scts.aspx 8 Feb 08)

The Schmidt-Cassegrain telescope is designed to be easy to manufacture and cost effective, by using spherical mirrors, rather than parabolic, which are much harder to manufacture. The typical problem with spherical optics is a distortion called spherical aberration. This effect causes the appearance of rings surrounding a point source, as illustrated in Figure 15. The Schmidt optic solves this problem by pre-distorting off-axis images so that they can be resolved onto the focal-plane by the mirror.

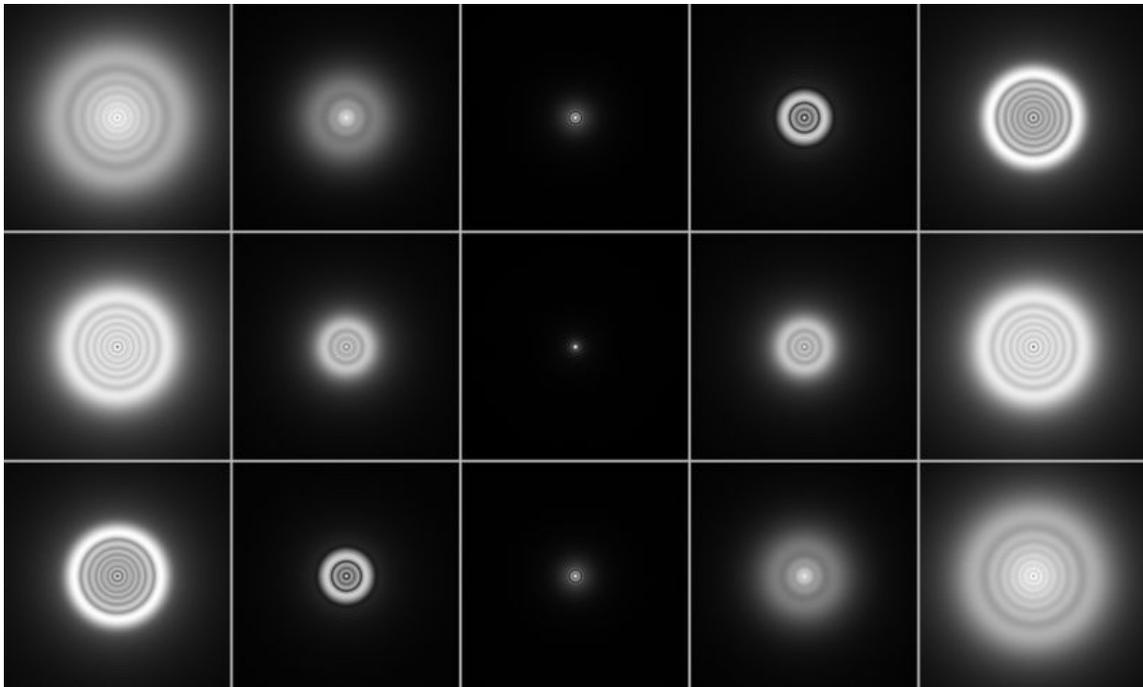


Figure 14. Effect of Spherical Aberration on a Point Source (From: Wikipedia http://en.wikipedia.org/wiki/Spherical_aberration 18 Jun 08)

There are, of course, drawbacks to this design. As shall be discussed in Section E. below, every additional element that is added to an optical train introduces an additional loss. The additional lens on the front of the telescope reduces the amount of light that makes it to the focal plane, necessitating either a higher energy pulse from the laser or a more sensitive focal plane. Also, the arrangement of the lens requires a significantly longer optical tube than is required by a traditional Cassegrain design. This increases the moment required for slewing. Fortunately, this is somewhat offset by the wider field of view, which may reduce or eliminate the amount of slewing required.

The Schmidt-Cassegrain design is not ideal for most LIDAR systems, but it may be useful for particular applications in which off-axis resolution is important.

D. TRANSMIT OPTICS

As discussed in Chapter III, the divergence angle of a laser is determined by the geometry of the laser cavity and the aperture size of the laser itself. Accordingly, it should be possible to build a laser to produce almost any divergence angle required without the use of any additional optics. It is not, however, always possible to have a

custom laser built for every application. Furthermore, there are practical limits to the size of laser cavity that can be manufactured or operated. Consequently, the beam produced by the laser may not match the beam profile required by the design.

Lasers emit their energy in a very tight beam along their principal axis. This is what makes them useful for LIDARs, but it may not always allow for the most flexibility. What if the design calls for a beam that sweeps back and forth through a defined search grid?

Both of these problems, and others, can be addressed by the use of a transmit optical train. In the first case, a beam expander can be used to spread the beam to provide a profile similar to that which would be produced by a much larger diameter laser, giving the beam a much smaller divergence angle. The second problem could be addressed through the addition of a scanning mirror or a spinning mirror. In each case, the path or profile of the laser beam is altered using additional mirrors and lenses.

E. OPTICAL TRAIN LOSSES

Unfortunately, no mirror reflects 100% of the energy that falls on it, and no lens transmits 100% of the energy that passes through it. As a result, every mirror or lens in both the transmit and receive optical chains contributes a loss to the system. These losses tend to be quite small, depending on the quality of the component, but they do add up. As noted above, even the simplest reflector telescope uses at least two mirrors, and most use more.

On the receiving side, this problem is further exacerbated by the energy levels inherent in the laser. A typical laser pulse for an SSA LIDAR can easily be in excess of a kW. Assuming a mirror with 99.9% reflectivity at the laser's frequency, the mirror is absorbing 1W per KW per pulse. Of course, the reason the power is so high is generally that the pulse is very short, not because the energy level in the beam is generally that high. Still, it is a substantial heat load on the mirror, and if absorbed in a sufficiently short pulse, can lead to thermal shock, cracking, discoloration, or warping.

V. DETECTOR ALTERNATIVES

A. LAYOUT ALTERNATIVES

The focal plane of the LIDAR can be one of two general configurations: single pixel and multiple pixel or area array. Each has advantages and disadvantages, depending on the mission, other components selected, and operational concept.

1. Single Pixel

A single pixel system is one in which a single detector is responsible for collecting all of the returning energy that is to be collected. Depending on the particular design, the field of view of the pixel may be greater or less than the area illuminated by the laser. If the detector's field of view is larger than the laser's, any energy returned from a target in the beam's path will be seen, provided the energy level is above the threshold required for the detector material. The position of the target within the beam, however, will be unable to be determined from a single pulse. The resolution of such a system relies on the width of the illuminating beam, potentially refined by scanning algorithms.

In this type of system, the angular position of the target is determined by knowledge of the laser's angle. The detector's field of view need not be precisely aligned with the laser's area of illumination, as long as it encompasses it. Accordingly, the alignment of the detector, while critical, is substantially less important than that of the laser.

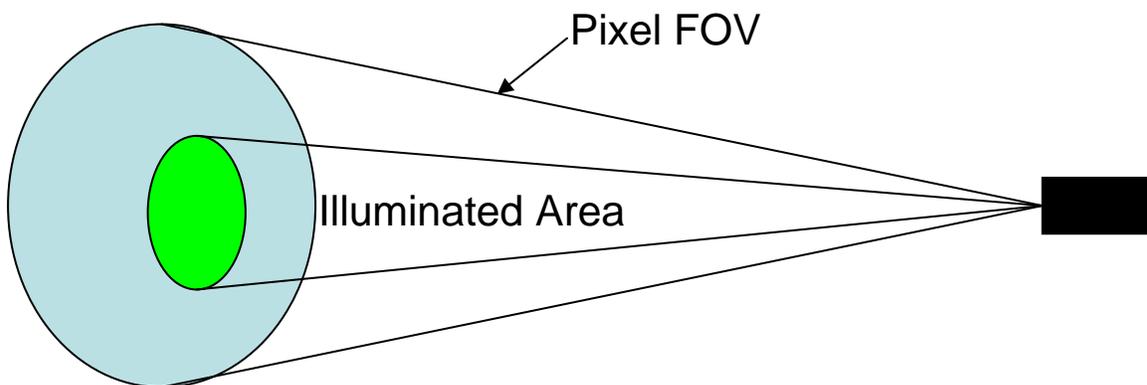


Figure 15. Pixel FOV > Laser FOV

It is also possible to design a system in which the detector's field of view is narrower than the area illuminated by the laser. In this case, the angular resolution of the system is improved, but the probability of detection on any particular pulse is decreased. An object may be illuminated by the beam, but it will not be sensed if it is outside of the detector's field of view.

Angular knowledge from this type of sensor relies on knowledge of the pixel's field of view rather than the area of illumination. Consequently, the detector's alignment is far more significant than that of the laser, though they must obviously be sufficiently co-aligned for the laser to illuminate the detector's field of view.

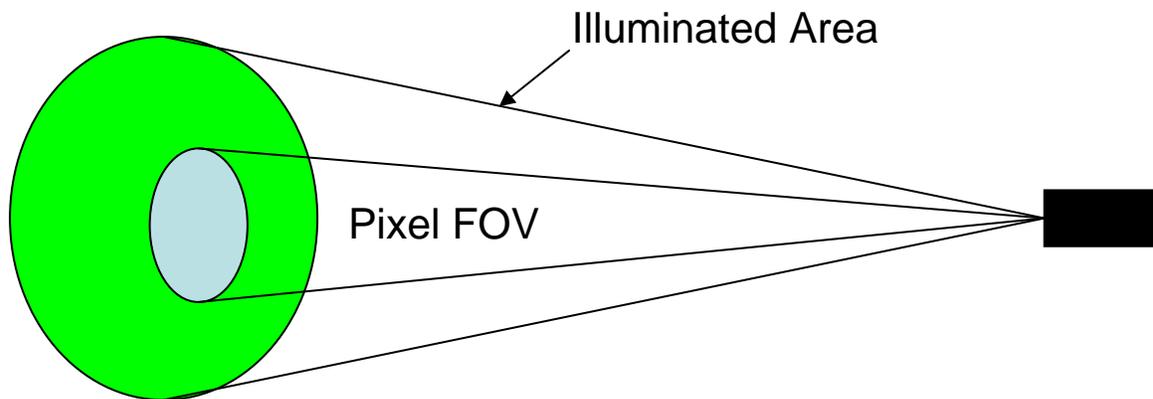


Figure 16. Laser FOV > Pixel FOV

A third possible variant, which is arguably a subset of the other two, uses a scanning mirror to redirect returning signals from various angles onto the single pixel. The pixel itself may have a larger or smaller field of view than the area illuminated, but the significant point is that angular knowledge of the scanning mirror, rather than the detector itself, becomes much more critical in this type of implementation. This variant will be discussed further in the next chapter.

Each of these configurations uses relatively simple hardware implementations and algorithms. The single pixel can be sampled at whatever rate is required for the necessary range resolution, or the sensor can be set to signal whenever a sufficiently large return is sensed. Detection can be accomplished with a relatively straightforward control loop, and simple hardware implementation.

2. Multiple Pixel

Multiple pixel systems utilize an array of pixels, rather than a single detector. Such implementations are necessarily more complex than single pixel systems, but they allow a greater degree of flexibility in how the laser and detector work together to detect and localize targets.

One application of multiple pixel focal planes is to resolve angular position within the projected laser beam. In this type of system, the laser illuminates a relatively large area, possibly using a beam expander or a laser with a large divergence angle. Narrower beams at long ranges would have similar effect. Angular resolution depends on the field of view of each pixel rather than particular directionality from the laser. As with a single pixel detector in which the pixel's field of view is narrower than the area illuminated by the laser, the positional knowledge of the individual pixels is far more critical than the positional knowledge of the laser.

Another application would allow the laser to scan a wide area while the presumably larger telescope and focal plane remain stationary. This concept will be explored further in the next chapter, but a brief explanation is in order for this chapter:

Because most lasers produce narrow beam illumination without the use of beam-expanders or other large lensing systems, and because the resultant beam can usually be easily redirected using small, lightweight mirrors, it may often be easier to move the beam through an area to be searched than to swing a focal plane and its attendant telescope through the same region. Accordingly, the focal plane can be designed so that its cumulative field of view covers the entire region to be searched, with different pixels picking up the return signals as the laser scans through the region. The advantages of this type of implementation over the scanning mirror and single pixel implementation will be discussed in the next chapter.

3. Advantages and Disadvantages

The primary advantage of a single pixel system is simplicity. Any signal received will be from the direction in which the system is pointing. As long as the laser and the pixel are pointed at the same area, noise from off-axis sources is minimized. The

processing algorithms and hardware required to implement such a system are drastically less than a multi-pixel system, and the problems of latency that, as we shall see, can plague multi-pixel systems is virtually eliminated.

The most obvious disadvantage of a single pixel system is that the angular resolution is constrained by that of the pixel or of the laser, depending on the implementation. This can be a significant drawback for the kind of long distance detections required by space surveillance applications, where even a narrow beam can spread over a significant distance. For example, the project discussed in Chapter IX requires that the LIDAR be able to detect objects at 1500 km away. At this range, a laser with a narrow divergence angle of $40 \mu\text{rad}$ would spread to an illuminated area over 120 meters in diameter. Keep in mind that this is a particularly narrow divergence angle. More typical lasers are in the $1000 \mu\text{rad}$ range. For many applications, this might be acceptable, but for our project, it was not. For systems used at shorter ranges or in which low angular resolution is acceptable, this would not present the same problem.

Single pixel systems are also, for obvious reasons, only capable of handling a single laser pulse at a time. From the time a pulse is sent to the target area until it is returned to the detector, the system must wait. If an additional pulse is sent during the intervening time, range ambiguity is an almost certain result. If two pulses are transmitted, but only one is received, which was it, the first or the second? In the example above, waiting for a pulse to return from a target 1500 km away would allow for a pulse repetition frequency of less than 100 Hz. It is possible to design a single pixel system that can overcome this range ambiguity issue, as discussed in the next section of this chapter. Unfortunately, the level of complexity required would significantly offset the principle advantage of a single pixel system: namely, its simplicity.

Multiple pixel detectors, while substantially more complex than single pixels, can greatly improve the angular resolution of otherwise identical systems. Furthermore, they can circumvent the range ambiguity question by allowing pulses sent at different times along different vectors to be resolved onto different areas of the focal plane. With a well planned scan pattern, such as those discussed in the next chapter, scan rates can be substantially higher than those of single pixel detectors, particularly at long ranges.

The disadvantages of multiple pixel systems are both more complex and more numerous than those of single pixel systems. Each of these disadvantages can be overcome or compensated for, but the methods used to do so only further increase the already complex implementation required of multiple pixel systems.

The greatest disadvantages of multiple pixel detectors are related to the technology used to form and read the pixels. This issue will be addressed at length in the “Technology Alternatives” section of this chapter, so we will not address them here.

Next in significance is the issue of alignment. As mentioned previously, single pixel systems can get by with detailed pointing knowledge of either the detector or the laser, depending on implementation, but do not require both. By extension, some amount of shift in the alignment of the non critical element over life can be accepted without any impact to the sensor’s accuracy. Multi-pixel systems are somewhat less forgiving in this regard.

4. Exotic Implementations

One way of getting around the problem of waiting for each pulse to return before sending out the next one is to use multiple lasers operating at multiple wavelengths. Similarly, a single multi-wavelength laser could accomplish the same thing. The trick, in this case, is to differentiate the different wavelengths when they return. This could be done in a variety of ways, some of which involve using more than one pixel, but still behave much like a single pixel sensor. Some possible systems are discussed below.

Filter wheel: Filters are discussed generically later in this chapter, but for this particular application, need only be understood to limit the wavelengths of light that can pass through them. This option will only work if the range from the sensor of the volume to be searched is well defined and relatively narrow.

This type of system would have a segmented wheel with different narrow-pass filters in each segment situated directly in front of the focal plane. The different wavelength pulses and the color wheel would be synchronized so that, when a pulse is expected to return from the desired search range, the appropriate filter is located in front of the detector. As can be readily deduced, the more segments in the wheel, the shorter

time any one can be observed, and the more likely any given return will be missed. In fact, if the timing is wrong, or the target is slightly too near or far, none of the returns will be detected, since they will all fall on a filter designed to block them.

Obviously, a designer must be very certain of the requirements before choosing such a system. Still, for some applications, such as detecting Geosynchronous spacecraft from low or medium orbit, where the possible ranges are narrowly defined, but the pulse return time is high, this type of system might make sense.

Prismatic systems: This type of system eliminates the range-gating issue inherent to filter-wheel systems, but at the cost of increasing the number of detectors. In this type of system, prisms located in the return optical chain redirect any received light differentially, depending on wavelength. Detectors are then positioned at the proper locations to detect the different return signals. Filters should still be used to reduce the noise from other light sources, though this isn't absolutely necessary. The obvious downside is that you can no longer get away with a single pixel detector, which means slightly increased cost and complexity. Still, one or two additional detectors in order to double or triple the pulse rate could be well worth the extra complexity and expense.

Multi-Junction detectors: A third possibility is using a multi-junction detector. In this type of detector, light of different wavelengths is detected at different depths within the pixel. This type of detector is already in use in the commercial world in the Foveon X3® line of sensors. This type of sensor has the obvious advantage of being able to both detect and differentiate between each of the various wavelengths on the same chip. The potential downside is the fact that, as currently available, each layer detects a fairly broad range of wavelengths, so noise from other light sources could be an issue. With proper filtering, sufficiently narrow detector bands, or both, this type of sensor may have a bright future in LIDAR applications.

B. TECHNOLOGY ALTERNATIVES

There are two basic competing technologies that are worthy of consideration for detector arrays.

The choice of detector technologies is largely a subset of array type. The advantages possessed by a Complimentary Metal-Oxide Semiconductor (CMOS) detector are largely negated for single pixel and linear array applications. In area arrays, the type of array selected depends on other factors, described below. In short, however CMOS allows for faster outputs from each pixel at the cost of higher complexity and, typically, lower fill factor, while Charge-Coupled Devices (CCDs) allows for higher fill factors and simplicity, at the cost of longer delays in outputs and higher losses due to charge transfer.

CCDs operate by absorbing photons, converting them to electric charge, then shifting the charge from pixel to pixel until the charge is collected at the output. The coupling between the pixels as the accumulated charge is transferred between them is what gives the device its name.

The principal advantage of this type of device is that only one output is needed for each row of pixels, rather than requiring a separate output from each pixel. This enables much simpler software and hardware architecture, simpler processors, and lower memory requirements. Another advantage of this type of device is that the detected charge is taken off the chip from the edge, via pixel to pixel transfer. As a result, no circuitry is needed on the surface of the device, leaving each pixel completely unobscured. This allows for completely square pixels and high fill factors, allowing maximum light collection.

Unfortunately, these advantages lead directly to the two principal disadvantages of this technology. The simplicity and fill factor are enabled by the charge transfer mechanism between pixels. This charge transfer, however, is subject to two main problems. The first is that, as with any electrical process, some loss is experienced each time the charge is transferred, ultimately making the device less efficient in detecting incoming signals, particularly at the low intensities some LIDAR systems require.

The second disadvantage is similar to the first. As the charge is transferred from pixel to pixel, additional photons can fall onto the focal plane, adding to the charge previously transferred from another pixel. This can lead to both directional and time-of-arrival ambiguities. This problem can be alleviated by shuttering or by obscuring some pixels, but either of these solutions would obviously make the loss of some returning signal much more likely.

After the charge is transferred to the edge of the CCD array, the resulting voltage or current, depending on the particular type of CCD, is measured, then digitized for use elsewhere. It is, of course, possible to keep the signal analog longer, but in the highly charged, high radiation, high thermal gradient environment of outer space, it is generally advisable to convert signals to digital as close to the source as possible. In doing so, it takes advantage of the interference and noise rejecting capabilities of properly constructed digital signal chains.

CMOS devices, on the other hand, can convert the output of each individual signal directly to digital without transferring charge, accumulating extra charge, or allowing any additional interference signal to impinge on the output. Herein lies the CMOS device's greatest advantage over the CCD: flexibility. Since the conversion is done directly from the pixel, each pixel can be individually addressed by the processor at any time, regardless of whether the adjacent pixels are sampled at all. Additionally, each pixel of interest can be sampled only when needed, and each can be set up to signal the processor whenever a return is detected.

Of course, as with any such advantage, it leads to its own disadvantages as well. Since the charge is detected on each individual pixel rather than from the edge of the array, circuit traces are required over the face of the pixel. As more functionality is added, such as on-chip A/D converters, interrupt signalers, and timing signals, more traces are required. As a result, the fill factor – the percentage of the array capable of detecting light – of CMOS devices is invariably lower than those of equivalent CCD arrays. The traces also tend to cause irregularly shaped pixels, rather than the even, rectangular pixels of a CCD array.

There are two methods of overcoming this problem. The first is the use of micro-lenses, essentially adding a lens on top of each pixel to gather and concentrate the light onto the light-sensitive areas of the chip. As mentioned in Chapter IV, however, each additional lens in the light path contributes to optical losses, so this approach is not ideal for applications requiring high-sensitivity to weak signals. The second approach is to use thinned, back-illuminated arrays. With this technique, the substrate of the CMOS chip is thinned or removed all together, allowing light to reach the photoactive regions of the chip from either side (Reich 2). This allows the circuit traces to be effectively moved to the back of the array, providing an unobstructed light path to the pixel. This technique allows the CMOS device to approach or even match the fill factor of an equivalent CCD device. The major drawbacks to this approach are the delicate process of removing the substrate material, possibly resulting in lower manufacturing yields, and the potential fragility of the resulting thin array. For one-off or low rate production items, as LIDARs tend to be, however, this may well be an ideal solution.

The other chief advantages of CMOS arrays in space applications, are that they have shown themselves to be inherently radiation-hardened, and tend to have low dark-noise counts. Rad-hardness is an obvious advantage for any space application. Dark-counts – signals produced by pixels as though they've been illuminated when they haven't been, usually caused by thermal effects – are most significant in systems requiring the detection of low return signals, and will be discussed further in Chapter VII.

A variant of CMOS APS of particular interest to long range, low return LIDAR designers is the Geiger-mode APS. In this type of sensor, each pixel is designed to send a signal pulse whenever they detect a photon. Like a Geiger-counter, the more photons they receive the more pulses they send out. The application of such arrays to systems which may only receive a handful of photons from a long-range target should be obvious.

C. WAVELENGTH CONSIDERATIONS

The material used for the focal plane is dictated by the wavelength of the laser used. As previously mentioned, the equation can work in the other direction, with focal plane material dictating the type of laser. In any case, the frequency response of the detector and the wavelength of the laser must be compatible.

1. Materials

The most common material for photo-detectors is silicon. As seen in the figure below, silicon detectors can “see” photons over the entire visible spectrum and into the near infra-red. The fact that most commercial and military applications are designed to detect these frequencies means that most production facilities are set up to produce these types of devices. Consequently, the widest range of available detectors and manufacturers will be available in this material. All other things being equal, selecting a laser which produced light in these ranges would be a good design choice.

Nonetheless, silicon detectors are by no means the only option. HgCdTe, InSb, and other exotic detector materials listed in the figure below are available, though at higher cost and requiring additional integration work, sometimes including extensive thermal control and cooling. Should the considerations in Chapter III drive you to select a laser outside of the silicon detection band, further investigation into these materials would be advisable.

One point to keep in mind: none of the materials depicted below will convert all of the received energy into signal, and some respond to less than 30% of the energy within their detection band. This signal loss must be taken into account when determining the laser power and aperture size to be used.

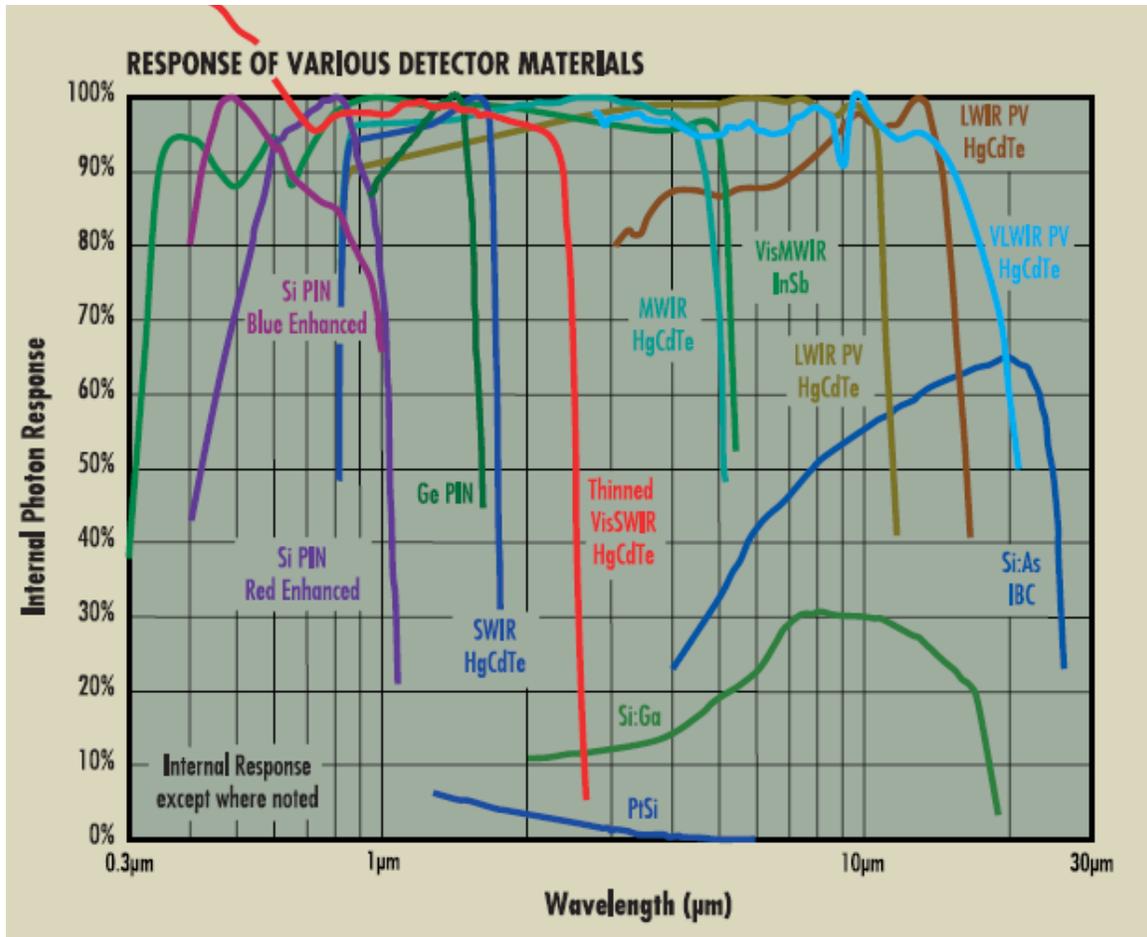


Figure 17. Detector response curves (After: Raytheon Vision Systems IR Wall Chart, 2006)

2. Filters

As discussed in Chapter III, lasers are the most monochromatic source of light available. The chief advantage this monochromaticity provides is that, while most bodies emit and/or reflect broadband light, the return signal from an illuminated LIDAR target will be at a nearly exact frequency. Assuming some relative motion between the sensor and the target, there will, of course, be some red or blue shift in the light, but at typical rates and light frequencies, the shift will be nearly undetectable, and need not be considered. This being the case, and given the fact that even the sun only puts the tiniest fraction of its light into any given frequency, it should be possible to detect a return signal against almost any background noise source. Generally, this is accomplished by filtering.

Filters work by absorbing and/or reflecting the frequencies outside the desired detection band. As a rule, reflecting filters can be more precisely tailored to exact frequencies, and are generally preferable for high energy applications. Absorbing filters convert the absorbed energy into heat, which can cause damage if enough light, from the sun, for example, is incident on it. Whichever type of filter is used, the narrower the range of frequencies passed the better. A properly designed filter can reduce the detectable bandwidth of an incident signal to less than 1 nm (Postava 613). A filter this narrow should eliminate almost all noise from other light sources, allowing the detector to “see” only the desired target.

Filters can be included at various locations throughout the image path. They can be placed as coatings onto the reflective or refractive surfaces of the telescope. They can also be stand-alone elements within the telescope or in front of the focal plane, or they can be placed directly on the focal plane itself. Any of these placements can be effective, but two locations present the most advantages.

The first advantageous location would be on the first refractive element of the telescope. Placement here prevents extraneous light from entering the remainder of the optical path. In the case of a Schmidt-type corrector plate, it prevents the extraneous light from entering the telescope at all. In systems that may image into or near the sun line, this has the obvious advantage of reducing the thermal load on internal components of the telescope and focal plane. The chief disadvantages of this placement are the size of the filter necessary, and likely exposure to contaminants, which may change the filter’s performance over time.

The second advantageous location is on or directly over the focal plane. This allows you to use the smallest possible filters, and puts the filters in the most protected location. The chief disadvantage of this placement is that, in the case of reflective filters, the light has to go somewhere after it reflects off the filters, and may cause stray light issues within the telescope. In the case of absorbing filters, it puts a potential heat load very near the thermally sensitive focal plane, which can cause additional noise or even damage.

D. PHOTOMULTIPLIERS AND IMAGE INTENSIFIERS

Depending on the detector material used, the strength of the signal to be detected, and the wavelength of the laser employed, it may be advisable to use a photomultiplier or image intensifier as part of the detector. A detailed discussion of the physics of photomultipliers and image intensifiers is outside the scope of this paper. For a general illustration of how they work, see the figure below.

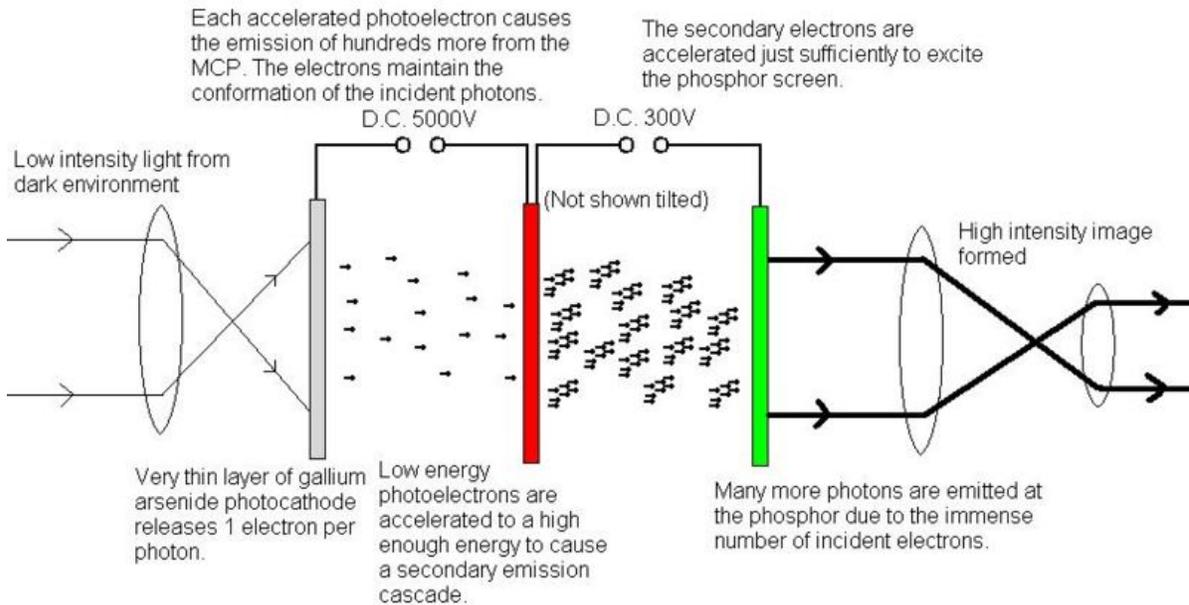


Figure 18. Photomultiplier Diagram (From: <http://en.wikipedia.org/wiki/Image:Photomultiplier.JPG> 9 Feb 08)

While photomultipliers do have significant drawbacks, image noise and power consumption among them, they also offer several advantages to the LIDAR designer.

The most obvious advantage of a photomultiplier is that they can take a weak signal and increase its intensity by several orders of magnitude. This is particularly helpful in the case of less responsive detector materials. The other possible advantage is that the front photo-cathode material can be responsive to one wavelength of light, while the detector on the back end can be responsive to another. In this case, a more exotic

material could be used on the front layer, to detect longer or shorter wavelength signals, and a more standard silicon detector could be used on the back end, potentially simplifying integration and reducing cost.

On the downside, additional components obviously add complexity. Now not only is the location, orientation and alignment of the focal plane important, but both the absolute and relative location, orientation and alignment of each layer of the photomultiplier are significant as well. For example, a signal which falls on one photosensitive pixel on the first layer could have its position shifted multiple times as it passes from layer to layer, which could result in significant angular location errors on the detector focal plane.

Furthermore, due to their very nature, image intensifiers tend to have significant dark-noise levels. Without significant consideration of the signal processing involved in separating legitimate signals from this noise, the false detections could easily overwhelm the actual returns, rendering the entire system useless.

E. SUMMARY

As can be seen from this chapter, nearly as many considerations must go into focal plane selection and design as into the rest of the components put together: the number and arrangement of pixels; the pixel technology used; the photo-detector material; filters; photomultipliers; A/D; and signal processing. Each of these choices, in turn, drives other choices and design decisions. Further advancements in the state-of-the-art are constantly appearing, so the system designer should pay particular attention to the materials and technologies available and applicable to the specific application. Chapter IX will provide an example of how a focal plane selection can be made.

VI. POINTING AND SLEWING REQUIREMENTS

Assuming that the sensor is not just intended to look for targets along a single bearing, it is necessary to scan the sensor to inspect a volume. When choosing a scanning method to employ, a wide variety of factors must be considered: the size of the volume, the relative velocity of the targets, the frequency at which the volume must be swept, the power of the laser, the type of focal plane employed, and many others. A full investigation of all possible scanning methods for all possible missions could easily fill a longer paper than this one. In this chapter, we will explore some of the pertinent issues and discuss some of the schemes that could be used.

A. SCANNING METHODS

One of the most important considerations to keep in mind when considering the scanning method to use is that, unlike terrestrial applications, or even most airborne applications, space-based SSA can involve targets that approach the sensor from virtually any direction at almost any relative speed. Furthermore, most of the orbits of interest are filled with both satellites and debris. Depending on the specific mission, all these targets may or may not be of interest. Before selecting the scanning method to be used, careful consideration should be employed in determining what size targets in what orbits should be detected. If, as in Chapter IX, the system will be used to detect targets in a relatively narrow volume on a limited range of trajectories, one type of scanning pattern would be used. A system designed to detect all objects passing within a certain range of the system would require an entirely different search method. With that consideration, let us consider some of the search patterns that could be used. Please note that, in some cases, the differences between these types of scans are somewhat arbitrary, and that they may be considered as variations on each other.

1. Raster Scan

A raster scan type of search is useful for searching a relatively narrow, conical or box-like region, though with some modification, it can also be employed for searching a disk or hemisphere of space, as we shall see. This type of scan works rather like the

electron gun in a Cathode Ray Tube television. The scanning beam is swept back and forth about one axis, which for convenience we will refer to as scanning along azimuth. At the end of each azimuthal sweep, the scan is moved slightly about a perpendicular axis, which we will refer to as shifting elevation. For most applications, the shift in elevation will be allowed to proceed from the “top” of the volume to the “bottom,” then reversed to scan back “up.” In this way, the pattern projected at any given distance from the sensor will be roughly rectangular, as in the figure below.

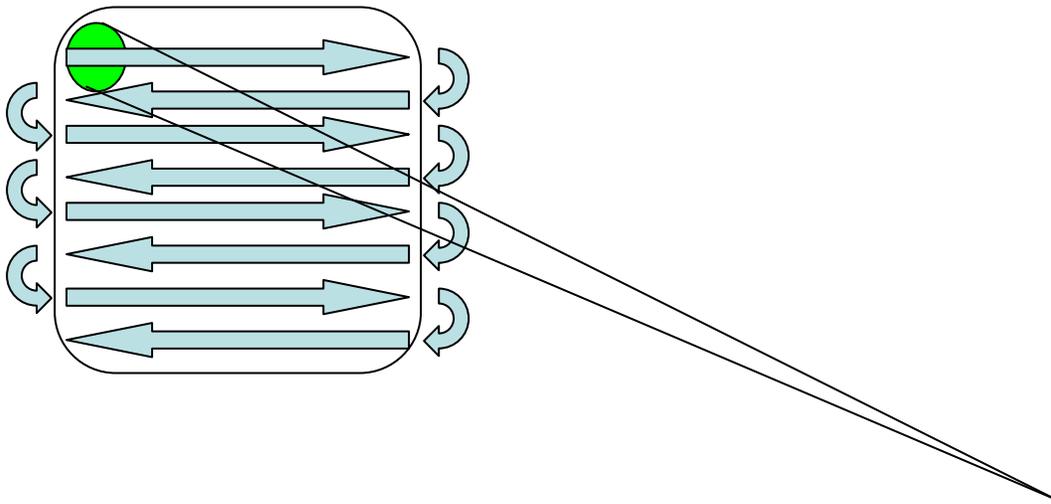


Figure 19. Raster Scan

If this pattern is modified by allowing the elevation to continue through a full 360°, the volume scanned will resemble a disk which is thinnest towards the center and gets thicker the farther out you go.

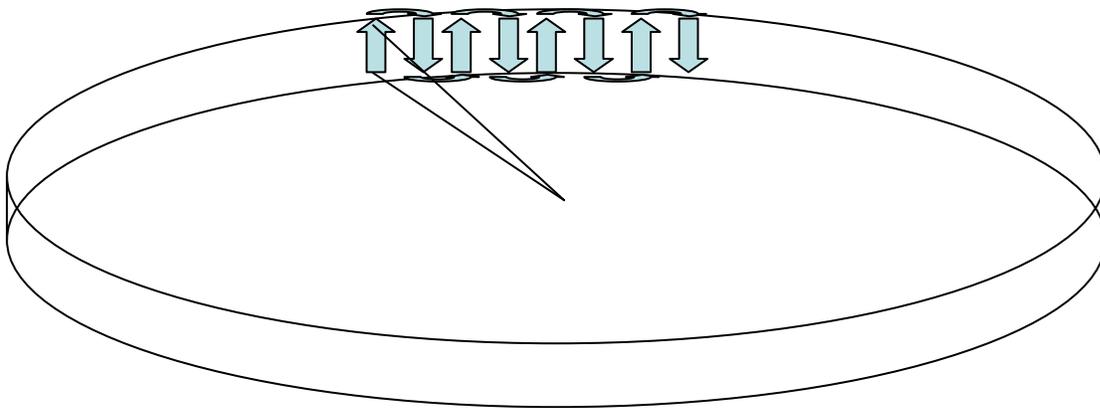


Figure 20. Raster Scan, Unconstrained in Elevation

If, on the other hand, the azimuthal sweep is allowed to continue in a full circle before changing the elevation, the volume searched begins to look like a partial hemisphere. If the elevation is allowed to cover a range of 90° , the volume searched will, in fact be a hemisphere, though at the “top” of the hemisphere, the scan will be virtually indistinguishable from the Spiral Scan, discussed below. If the elevation can change 180° , a full sphere can be swept. Obviously, other variants on this scheme would allow for smaller sections of a sphere to be searched

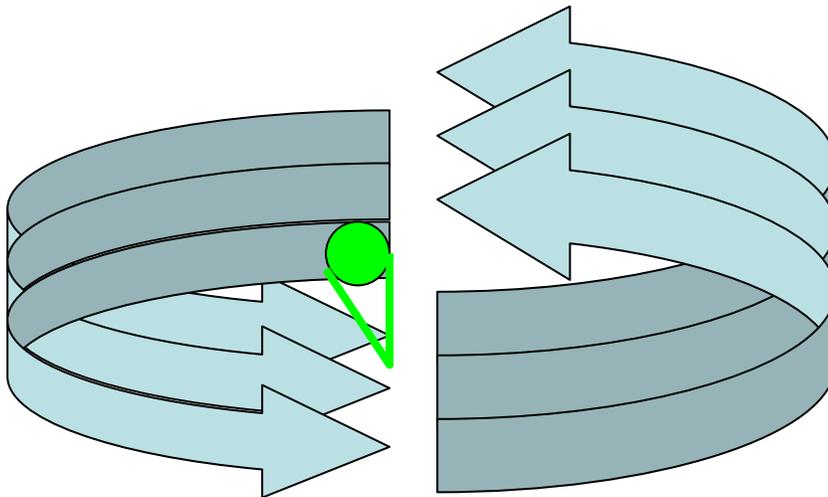


Figure 21. Raster Scan, Unconstrained in Azimuth

2. Spiral Scan

While the Raster Scan can be most easily thought of as a Cartesian type of scan, with scans along the “X” axis or Azimuth, and shifts along the “Y” axis or Elevation, the Spiral scan can be more easily conceived as a radial type of scan, with scans along the angular and shifts along the radial. This type of scan is best suited for searching circular, conical volumes. As noted above, a raster scan unconstrained in azimuth is very similar, if not identical, to a spiral scan when near the “top” of the hemispherical area to be searched. In both cases, the scan moves in a circular pattern, spiraling into the center, then spiraling back out. This type of scan is particularly ideal for searching for a target which is expected to be at or near a known position. The sensor begins by searching at the known position, then spiraling out to search the surrounding area.

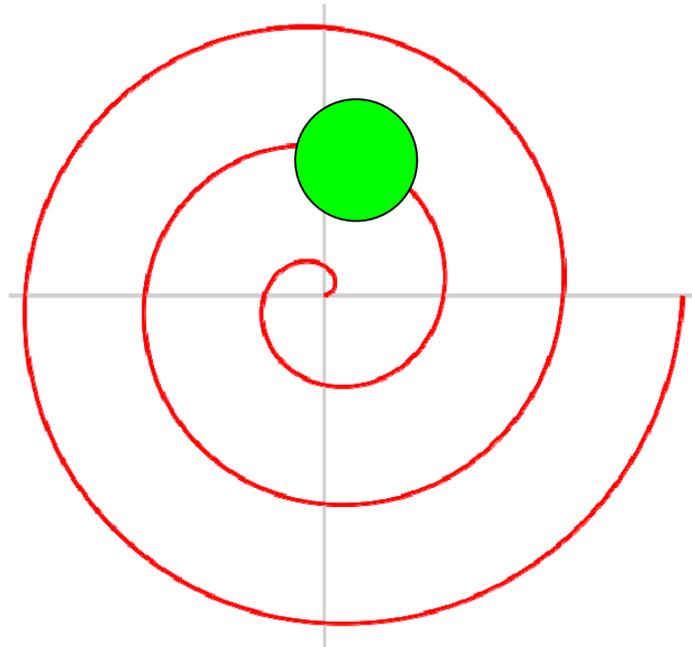


Figure 22. Spiral Scan (After: Wikipedia http://en.wikipedia.org/wiki/Image:Archimedean_spiral.svg Feb 08)

3. Planar Scan

This type of scan could be used to detect all objects “passing through” a detection plane, as illustrated by the figure below. It would be particularly well suited for a spin-stabilized satellite. Essentially, the sensor is pointed perpendicular to the axis of rotation of the vehicle, and sweeps out the plane defined by the axis vector. Of course, since the satellite is moving while this occurs, the search pattern is only planar in the satellite’s reference frame. From an inertial perspective, the searched area is more like a screw pattern about the direction of motion.

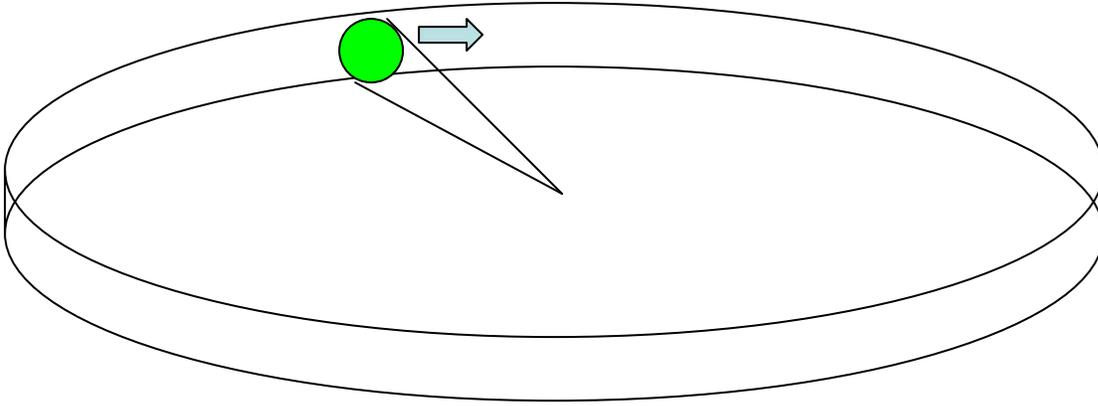


Figure 23. Planar Scan

4. Random Scan

This type of scan would be most appropriate for a small sat or secondary payload implementation. In this implementation, the laser would either pulse at a pre-determined rate based on power and thermal constraints or by the range within which the LIDAR is intended to search. It could also pulse whenever another sensor detects an object within the LIDARs field of view. In either case, the LIDAR will essentially collect targets of opportunity, as objects happen to pass within the detection window of the sensor, or when the sensor happens to be pointed at an object

B. KNOWLEDGE VS. CONTROL

One point which must be understood by any space based sensor designer is the difference between pointing knowledge and pointing control, and how much of each is required. Depending on the design and application, some systems require precise pointing control to ensure that the system is aimed in exactly the right location, sometime for an extended period of time. Other systems may be able to operate with a less precise control system, provided that their pointing knowledge is sufficiently refined. Without careful consideration of the manner in which a system is to be employed, the designer can easily develop a system with more precise pointing control than necessary, but an insufficient amount of pointing accuracy. Some examples below should illustrate this point.

For some applications, it is necessary to control precisely where the sensor is pointing for long periods of time. High resolution staring sensors like the Hubble Space Telescope or the now in development James Webb Space Telescope need to be pointed precisely at distant objects for long periods of time. Any movement around that position can result in smearing or loss of resolution. Obviously, such a precisely pointing system must also have equally precise knowledge of where it is pointing. Having a system that can control its pointing position to the nearest nanoradian, but can only determine its position to the nearest milliradian is like navigating with a differential GPS that is accurate within one meter using a map that is only accurate to the nearest kilometer. The precision is nice, but not particularly useful.

A long range, single pixel LIDAR would need a control system capable of keeping the detector pointed precisely at the illuminated area for whatever time is required for the pulse to return from the target. If the field of view of the sensor and the area illuminated by the laser are not overlapping when the signal returns, no detection is possible. Of course, an equally accurate pointing knowledge system would also be essential, since the ability to hold steadily on a point in space isn't terribly useful without being able to tell which point to hold steadily on to.

On the other hand, a sensor intended to detect close-in objects, or an area array type sensor, can often afford to have a less precise control system, provided that the pointing knowledge is sufficiently precise. To understand this possibility, the following example may prove useful:

Assume a LIDAR is designed to search a narrow but long-range volume of space. The laser can be swept through the volume using a scanning mirror, and the telescope and area array focal plane are designed to encompass the entire volume within their field of view. For the sake of simplicity, assume the pixels of the detector are perfectly square, with a fill factor of 100%. This system sends pulses to various locations within the volume, using a spiral or raster scan. For the purposes of illustration, assume that the control system on the sensor is insufficient to hold the focal plane completely still for the length of time required for a pulse to reach its target and return, but is sufficient to keep the search volume within the field of view.

In this case, each pulse can return from a slightly different angle, relative to the detector, than that in which it was transmitted. The returning signal may well land on a pixel several rows or columns away from the one which was pointing at the illuminated area when the pulse was transmitted. If the pointing knowledge is sufficient, however, it doesn't matter where the focal plane was pointed when the signal was transmitted. The system simply notes the direction from which the signal was received and compares it to the directions in which pulses were known to have been transmitted. In this way, as long as the pulses are sufficiently separated in angle, multiple pulses can be "in flight" simultaneously without introducing range ambiguities, and without requiring an overly precise control system.

Of course, the requirements for each system must be considered. As a general rule, however, pointing knowledge is at least as important as pointing control, if not more so.

C. ATTITUDE AND POINTING

A concern of particular interest to space-based LIDAR systems is the interrelationship between attitude knowledge and control of the spacecraft, and pointing knowledge and control of the LIDAR. The two are always linked and interdependent, but the degree and type of linkage can vary widely.

The simplest type of relationship between the two is a system which is mounted in a fixed position on the spacecraft. In this type of system, attitude knowledge and control are virtually identical to pointing knowledge and control. The only disconnects between them are errors in alignment between the system and the spacecraft, and the stability of that alignment. Thermal changes, vibrations, and the fact that all objects are, to some degree, flexible, means that this alignment will never be perfect, or perfectly stable, but it is possible to reduce these errors to an acceptable level. What level is considered "acceptable" depends on the system design.

The next higher level of complexity involves a system wherein the LIDAR can move relative to the spacecraft, but nothing moves within the LIDAR, and pointing knowledge is determined relative to the spacecraft. In this case, additional errors in

pointing knowledge come from the actuators used to point the LIDAR relative to the vehicle, the positions of which are imperfectly known. Again, these errors can be accounted for and minimized, with a proper error analysis, but they must be considered.

More complex still is a system in which the LIDAR moves relative to the spacecraft, nothing moves within the LIDAR, but the LIDAR has its own attitude determination system, separate from that of the spacecraft. In this case, the attitude knowledge and control of the spacecraft is still significant, since the sensor and the vehicle are still connected, and move relative to each other. On the other hand, errors in spacecraft attitude and actuator knowledge can be compensated for by the sensors own attitude determination system. Changes in spacecraft attitude can be treated as perturbations to the sensor control loop, and treated accordingly. Obviously, such a system can be substantially more complex than those discussed previously, but the pointing knowledge and control of the system can be considerably better in exchange.

A different type of complexity is introduced when components within the sensor are able to move. Scanning mirrors are the most likely components to move relative to the rest of the sensor, but systems in which the laser, telescope, and/or focal plane move are also conceivable. Each additional moving component can introduce additional error into the pointing knowledge and control, though careful design can compensate for these errors in many cases. In the design described in the “Knowledge vs. Control” section above, small errors in scanning mirror alignment knowledge can be mitigated by more precise knowledge of the focal plane and telescope alignment. Note that moving components can be added to each of the designs described above, thereby increasing the sources of errors to be considered in analyzing the design.

Overall, each of the design variations discussed above have their own advantages and disadvantages, depending on the manner of employment and details of the design. The important thing to understand is that each source of error must be considered and accounted for when designing and analyzing the system.

VII. SOURCES OF NOISE

To this point, we have considered only the signal transmitted by the laser, reflected by the object, captured by the telescope, and measured by the focal plane. It is vital to understand, however, that various sources of noise, both within the sensor and without, will impact the LIDARs ability to detect objects of interest. In this chapter, we will consider the most significant sources of noise, their relationship to the signals returning to the detector, and the design considerations that flow from that relationship.

A. INTERNAL SOURCES

There are several potential sources of noise within the sensor, the impact of which varies depending on the type and design of the sensor. One source only affects particular system designs in which the pulse is transmitted and received through the same set of optics. The other applies to every type of LIDAR discussed to some degree.

1. Laser

In systems where the laser is transmitted through the same telescope used to detect returning signals, the fact that no set of optics is perfectly transmissive or reflective, or perfectly aligned, means that some of the laser light will, be reflected back to the detector unless some sort of physical shutter is used to prevent this. Obviously, the amount of noise reflected back to the focal plane, and the subsequent impacts of this return on the performance of the sensor will vary widely depending on the exact configuration and operation of the LIDAR. Different telescope designs will tend to reflect back different amounts of light, and different focal planes and processing algorithms will respond differently to the light that is reflected. Detailed analysis of the specific design, to include ray-trace models and/or actual illumination of engineering units would be required to accurately evaluate the impact of this noise source on any given design. Designs in which the laser and detector do not share the same set of optics are not subject to this noise at all.

2. Electronic Noise

Several potential noise sources exist within the electronics of the system. Thermal noise, Dark Noise (a subset of thermal noise), quantization noise, and other minor noise contributors must be accounted for and minimized or compensated for

a. Thermal Noise

As with any electronic system, some attention must be paid to thermal noise within the electronics themselves. Whenever a signal being handled by the system is digital, the system design must ensure that the difference between the levels of the digital system is sufficiently wide to differentiate between them with the addition of noise. This is extremely straightforward and is necessary for any digital system.

When the signal is analogue, however, any noise can alter the energy level detected and subsequently processed within the system. This noise is typically Gaussian in nature, and can be represented by the equation:

$$\sigma_v^2 = \frac{2(\pi kT)^2}{3h} R \quad (0.7)$$

Thermal noise is a reality for every electronic system, and can be dealt with using a variety of standard methods, including shielding and reducing the temperature of the system (Carlson 372).

b. Dark Noise

In any photo-detector based system, a source of noise that must be dealt with is dark noise. Dark noise is caused by the thermal motion of electrons in the photodetector, and is a function of the temperature and detector materials. Overall, the cooler the detector, the lower the dark noise, though specific materials and detector technologies can substantially impact the noise level. The chart below shows the dark current levels of different materials at different temperatures, including various cooler technologies capable of achieving those temperatures.

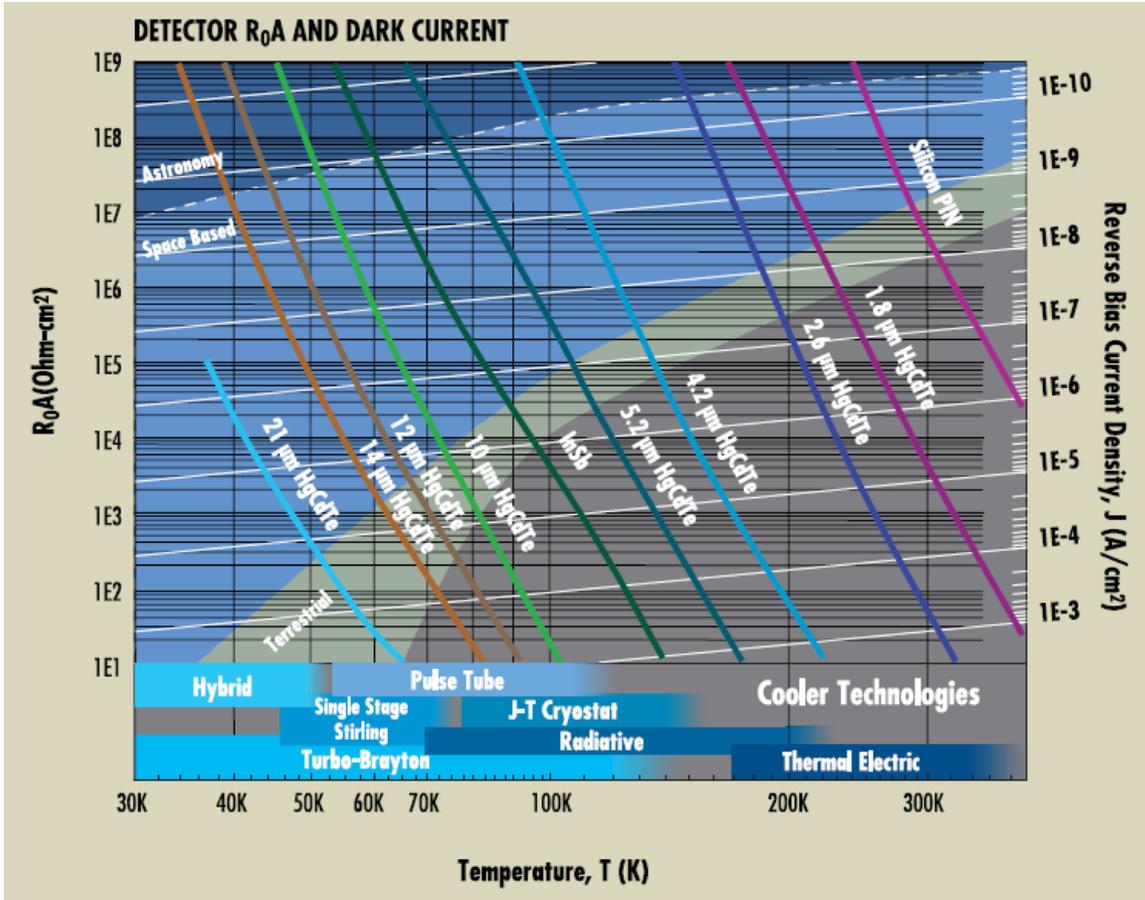


Figure 24. Dark Noise Current (After: Raytheon Vision Systems IR Wall Chart, 2006)

Dark noise generally appears as random speckle in video images, In a LIDAR application, particularly one in which single photon detection is possible, dark noise can easily appear as a false detection. Reducing the dark current obviously entails choosing a detector technology that meets the wavelength and quantum efficiency requirements for the system, which will also be the least susceptible to dark current, then keeping the detector as cool as practicable. Shortening the window during which a return pulse is expected, and carefully screening pulses for conformance with expected signal strength can reduce the likelihood of false detections. The best way to eliminate them, however, is to pulse the target multiple times and watch for the multiple returns. The chances of multiple pulses being false detections are substantially lower than for a single pulse.

c. Quantization Noise

Quantization Noise is caused by the conversion of “continuous” analog signal data being converted into discrete, quantized digital data in the Analog to Digital Converter (ADC). In systems capable of detecting single photon signals, this is almost a non-issue, assuming a carefully designed system. The least-significant bit (LSB) of the ADC is simply set to match the signal produced by a single photon, itself a quantized value, and any level of signal received, provided its intensity is not greater than the highest level the ADC can convert, should be properly transmitted.

Systems using substantially stronger signals or time-delay-integration are much more likely to have signals which are, essentially, continuous, and some impact from quantization noise will be seen. In this case, the usual practice is to set the LSB value equal to the overall system noise floor. This effectively digitizes the signal at a resolution which maintains the signal to within the accuracy possible due to other internal noise sources (Ahmed 318-321).

In short, in a properly designed system, this noise source must be accounted for, but should be one of the least significant contributors to system noise.

d. Signal Processing Noise

Related to quantization noise, signal processing noise is caused by the act of converting an analog signal into digital. This noise source is dependant entirely on the ADC utilized, and can be minimized by using the lowest noise ADCs available.

B. EXTERNAL SOURCES

1. In the Field of View

One element missing from the LIDAR equations in Chapter II is the impact of illumination from other sources within the field of view. If a light source or brightly illuminated object is going to be present in the field of view of the sensor, it must be accounted for in both component selection and the operational design considerations.

The simplest way to calculate the amount of light from the source that can interfere with the sensor is to determine the spectral irradiance of the light falling on the

aperture, calculate the energy entering the aperture, and converting the result to number of photons. Since the brightest likely interference source is the sun, we will use the solar spectral irradiance curve for our example.

Because, as discussed in Chapter III and will see further in Chapter IX, one of the most widely used high-powered lasers is the Nd-YAG laser, which emits at 1064 nm, we will use it as our example. The sun's spectral irradiance, which is the amount of light falling on a surface, at 1 AU, at 1064 nm is approximately 0.65W/m²/nm (SORCE Interactive Data Access). Assuming a 1 nm filter, as discussed in Chapter V, and a 1 m² aperture, as discussed in Chapter IV, 0.65 W of light at 1064±0.5 nm would be focused on the focal plane. Converting this into photon counts, that means that 0.65 J of energy is falling on the focal plane every second. Converting this into number of photons, using the equation:

$$E = \frac{hc}{\lambda} \quad (0.8)$$

Where $\lambda=1064$ nm, this means that approximately 3.5×10^{18} photons per second are falling on the focal plane.

Clearly, this is a very large number of photons, particularly in systems where only single-digit photon returns are detectable. Fortunately, as this is the sun, it represents the worst case for interference, short of another laser of the same wavelength pointing into the aperture. Accordingly, any other reasonable target will be many orders of magnitude less intense. For instance, light from Alpha Centauri is more than 10 orders of magnitude less intense than the sun. If you must search directly into the sun, however, several options are available to mitigate this noise.

The first, simplest approach is to shorten the pulse width of the sensor. Since the sun puts out relatively constant-intensity light (barring solar flares or coronal mass ejections), the number of photons arriving per unit time is also relatively constant. Consequently, pulse length is inversely proportional to signal-to-noise ratio. A millisecond pulse reduces the number of photons by three orders of magnitude; a nanosecond pulse by nine. For detecting objects in line with the sun, this is helpful, but insufficient.

The second approach again relies on the relatively constant nature of solar emissions. With a sufficiently advanced focal plane, as discussed in Chapter V, the steady-state noise from the sun, or any other constantly illuminated object, for that matter, can be subtracted out, to note the intensity spikes of the signal, when it is returned. Obviously, this method is less effective on varying noise sources such as flashing lights or tumbling objects, but those sources will tend to be much less intense than the sun. Slowly varying light sources can still be adapted to with sufficiently fast processing.

A third method is effective if, rather than directly in line with, or collocated with the noise source, the target is nearby but within the same field of view. In this case, and again, with a sufficiently advanced focal plane, the special separation between the signal and the noise can be used to, again, allow the processor to ignore the noise.

The remaining methods for reducing received noise are the same as those for reducing stray light on any telescope: coating the interior of the telescope with light-absorbent coatings, placing knife-edge cutout rings within the barrel, using anti-reflective coatings on any lenses, and doing stray-light analysis or testing on the system. In this way, only light within the sensors field-of-view must be accounted for.

In summary, the best way to avoid received noise is to keep strong light sources or reflectors, such as the sun, the moon, and the earth, out of the sensor's field of view. If the mission precludes this option, the signal to noise ratio can be improved by increasing laser power, shortening the pulse, using steady-source subtraction on the detected light, or searching near, but not directly at, the light source; furthermore, any steady-state noise source that doesn't saturate the sensor can generally be ignored with the proper algorithms.

2. Off-Axis Sources

As with reflected laser noise, the effect of off-axis noise is highly dependant on the geometry of the optics used to focus the signal on the detector. Also known as stray light, the off-axis source effects the signal when light from outside the pixel's normal field of view is reflected within the telescope to fall on the detector. The degree to which

any given geometry is subject to this noise source is best determined by conducting ray-trace analysis or actual testing of the optics. Good design practices, however, can minimize the likelihood of impacts by this phenomenon: knife-edge cutoffs within the optical train, light-shades extending beyond the aperture, non-reflective coatings within the optical tube, and anti-reflective coatings on any transmissive optics can all minimize the likelihood of off-axis light being reflected onto the detector. With a properly designed telescope, this noise source should be largely, if not completely avoided.

THIS PAGE INTENTIONALLY LEFT BLANK

VIII. SYSTEM INTERACTIONS

A. POWER REQUIREMENTS

The power requirements for a sensor of this type will be driven most significantly by duty cycle and concept of operations. A LIDAR which is always on, seeking out new contacts and updating old tracks, will generally require far more power than one that only comes on to image targets of opportunity or to evaluate tracks based on external cuing.

1. Always On

An “always on” system, while requiring the most substantial Electrical Power System, is actually the easiest to design. Simply sum the average power required by all system components, excluding backups that are kept on cold standby, and design your power system to handle this load. This type of system will likely be a multi-kilowatt system, but it will be a very straightforward design.

2. Predicted On

This type of system would be designed to inspect or track satellites at relatively predictable intervals. Such a mission might include inspecting a satellite whenever it comes into range, or updating tracks on a well-defined set of satellites on a regular basis. The total power requirements for this satellite would be much more modest, compared to the “always on” system, but a bit more work must be done to calculate those requirements.

Because this type of system is used only intermittently, the system can be turned off or placed in standby between engagements. An individual analysis would have to be done based on the periodicity and length of the engagements to determine whether off or standby is more efficient. For engagements that are very close together or very far apart, off is probably the better choice. If they are very close together, the system won't have long enough to cool sufficiently between engagements to worry about keeping it warm. If they are very far apart, it is likely more efficient to let the system get cold and warm it back up before using it again. Unfortunately this calculation would be very system and operation specific.

The average power requirements are fairly straightforward: average time on per orbit \times power requirement while on + average time on standby in orbit \times power requirement while on standby. The trick comes in predicting the battery requirements. How many times during any given orbit will the system be on? This must be calculated for the worst-case orbit, not the average orbit.

Further complexity is added if the events for which the system is designed are predictable in the near term, but not in the far-term. For instance, if a satellite is to be tracked every time it comes within a certain distance of the sensor, the times at which it should pass by can be predicted quite accurately a day or so in advance. A year in advance, however, such a prediction would be meaningless. If the sensor is tasked to track five different satellites in five different orbits, it may work out such that the satellite only sees each of them once a day, and never two on the same orbit. Based on this, the power system could be designed to provide power for one engagement per orbit. Two years later, however, it might pass three of those satellites on one orbit, and the other two satellites five orbits later. If the batteries are designed to handle only one engagement per orbit, the LIDAR will begin to miss engagements, shorten the lifespan of the satellite by discharging the batteries too deeply, or possibly both. Either substantial margin needs to be built into such a system, or it has to have an operational concept that allows it to miss engagements from time to time without failing its mission.

3. Unpredictable and Intermittent

This type of system might be designed for studying unannounced launches, short-notice collision hazards, and other such unexpected phenomena. A sensor such as this may be unused for long periods of time, then be tasked on very short notice, drawing massive amounts of power for a few minutes, then go dormant again for days or weeks.

The challenge in this case is to correctly determine and understand the timeline of expected engagements. If the anticipated timeline requires instantaneous full-power capability at any time, then it will be necessary to budget power to keep the system at operating temperature at all times, which will likely be a substantial load. If, instead, the expected timeline provides for several minutes warning, then careful consideration of the warm-up requirements for candidate lasers must be made.

As with the “predicted on” case, average expected power use will drive the power generation requirement, and expected engagement profiles will drive power storage requirements.

B. THERMAL REQUIREMENTS

For all their excellent characteristics, lasers are notoriously inefficient. Wall plug efficiencies of 40% are considered exceptionally high, and efficiencies of 6% aren’t considered particularly low. All the power put into a laser that doesn’t come out of the emitter is dissipated as heat, which must be disposed of somehow. As with power, the operational concept and duty cycle plays a significant role in this area.

1. Always On

As with power, the “always on” scenario provides the heaviest load, but the easiest design. Simply multiply the average power required by one minus the system efficiency, and design your system to radiate at that rate. The only real difficulty comes in accounting for modes of operation, such as “safe mode,” in which the system may be turned off unexpectedly. Since the amount of heat emitted by the sensor is likely a substantial portion of the total heat produced by the spacecraft, care must be taken to ensure that the spacecraft will remain within its expected temperature range with that source removed.

2. Predicted On, Unpredictable and Intermittent

In each of these cases, the problem is how to deal with irregularly timed pulses of large amounts of heat separated by long periods in which little or no heat is produced by the system. The simplest method is to employ some sort of heat sink, designed to absorb the heat load without increasing its temperature too greatly, then to release the heat more slowly, so as not to overwhelm the spacecraft’s thermal control system. Such a heat sink may be a solid material with high thermal capacity, such as a slab of aluminum, or some sort of phase change material, chosen to change phases at the desired operating temperature. As with power, it is vital to understand the expected duty cycle in order to

design this heat sink. For a system that is always kept warm, the difference in thermal load between on and off may not be significant, so a design similar to the “always on” scenario may be used.

C. PROCESSING REQUIREMENTS

The processing requirements for a LIDAR system depend heavily on the individual system design. A simple single-pixel single-pulse LIDAR like that described at the beginning of Chapter II requires very little processing power and a low data rate. The only real challenge to such a system is the precision of the clock, which determines range resolution. The only other requirement is to calculate the time between pulse transmission and reception and to divide the result by a constant. If the sensor can be steered independently of the spacecraft bus, the direction in which the target is detected must also be calculated, though this could easily be handled by the Guidance, Navigation and Control (GNC) system.

On the other hand, a multi-megapixel focal plane system with a beam-steering mirror and multiple-pulse bursts may require powerful processors, perhaps parallel processors, with high data rates throughout the system. Multiple pulses must be tracked and the angle of the mirror at transmission must be both set and remembered. The angle of arrival of the return pulse must be compared to the direction in which various pulses were sent. Search schemes must be developed and implemented, and contacts may need to be tracked over time.

Designing the control system for such a LIDAR could easily be a thesis itself and, as such, lies outside the scope of this paper. It is, however, a significant portion of the design of such a system, and must be considered when developing a design.

IX. POTENTIAL IMPACT ON OTHER SPACECRAFT

Obviously, when designing a sensor which will intentionally illuminate other satellites with high-power laser pulses, the impact that such illumination may have on those satellites must be considered. For instance, at very close ranges, lasers of the power we are discussing are capable of ablating materials with which they come in contact. At ranges more likely to be encountered in the course of carrying out an SSA mission, these lasers could damage the focal planes of imaging satellites or interfere with satellites using laser communications. Each of these will be briefly considered below.

A. THERMAL EFFECTS

These effects are due to the fact that lasers can focus large amounts of energy very rapidly into very small areas. Given a small enough spot size and enough energy in the pulse, and it is possible to deposit enough energy to weaken, melt, or even vaporize the object illuminated. To determine the risk of this occurring, the spot size at the closest expected distance must be calculated. For precise results, the thermodynamic and physical properties of the material to be illuminated should be known, though common spacecraft construction materials can be considered to obtain a good approximation. Then the following calculations should be carried out:

Multiply the specific heat capacity (J/kg·K) by the area illuminated (m²) and thickness of the material (m). Divide the result by the density of the material (kg/m³). This result will give you the energy (J/K) required to raise the temperature 1K. Divide the energy-per-pulse (J) by this number and multiply the result by the expected absorbance for the wavelength indicated. The result will tell you how much the temperature will increase due to a single pulse.

Example:

Pulse Energy = 0.5 J

Beam Cross Sectional Area = 100 cm²

Material = Aluminum sheet

Specific Heat Capacity = 900 J/kg·K

Thickness = 5 mm

Density = 2700 kg/m³

Expected Absorbance – 5% (95% Reflected)

$$900 \frac{J}{kg \cdot K} \times .01m^2 \times .005m \div 2700 \frac{kg}{m^3} = 1.67 \times 10^{-5} \frac{J}{K}$$

$$.5J \times 5\% \div 1.67 \times 10^{-5} \frac{J}{K} = 150K$$

In this case, the illuminated section of aluminum would increase in temperature by 150 K in the time of a single pulse. Multiple pulses, a smaller beam width, thinner material or material with lower thermal capacity would substantially increase this amount.

Once this information has been calculated for a particular LIDAR, a “keep out” zone can be developed. Thereafter, anytime a spacecraft is expected to pass through the zone, the illuminator should be pointed elsewhere or placed in standby until the risk of damage is past.

B. FOCAL PLANE DAMAGE

As with thermal effects discussed above, damage to the focal planes of other satellites can also be caused by the intensity and directionality of the beam. This problem is compounded by the fact that focal planes are, by design, sensitive to light energy. As a result, they can be damaged by much lower illumination levels than are required for physical effects. On the other hand, since imaging satellites tend to be extremely directional, a few simple precautions should avoid most potential problems in this area. As long as the imaging sensor and the laser are not pointed directly at each other, no damage should occur. Since most imaging satellites will be pointed at the earth when not in “safe mode,” the simple expedient of not illuminating known or suspected imaging satellites while your sensor is located between them and the earth should solve most problems. Informing the operators of such satellites of the nature of your payload, if possible, should alleviate the rest.

It might, at first glance, seem that selecting a laser which operates at wavelengths not generally detected by remote sensing satellites would help to avoid this problem altogether. Unfortunately, at the power levels required to do anything more than detection or imaging at close range, the pulses would quickly burn through any optical filters (see thermal effects above) and damage the underlying detector anyway.

C. CROSSLINK INTERFERENCE

With the requirement for data throughput constantly increasing, more and more work is being done in the field of space-based laser communications. NASDA's GOLD and OICETS programs, the ESA's ARTIMIS, the French SPOT 4, as well as various U.S. programs have all explored and utilized laser cross links experimentally. The success of these experiments indicates that constellations of satellites communicating with each other and the ground via lasers are just around the corner. Fortunately, most such satellites will be in geosynchronous or highly elliptical orbits, so burning out their detectors will be highly unlikely. Unfortunately, the power requirements for an illuminator that needs to bounce a substantial amount of energy off another satellite are significantly higher than those required for a one-way data-link, so any laser receiver illuminated by one of our beams would likely see its signal-to-noise ratio driven rapidly to something much less than one.

Ideally, we could select illuminators with wavelengths significantly different from those used in the crosslink and eliminate this problem. In the real world, however, many of the characteristics that make a laser attractive as an illuminator make that same laser attractive for space-based communications. Furthermore, each of the experiments to date has used a different wavelength, and other wavelengths are still under consideration for future use. Until such a system is actually built, any attempt to address the problem in this manner would be premature. Obviously, having multiple wavelengths to choose from would help to alleviate this problem.

In the unfortunate event that a space-based LIDAR and a laser communications constellation wind up using the same wavelength, the work-around would be the same as that used for imagery satellites. As long as the illuminator does not point directly at the

communications satellite, neither will see the other. This should not prove too difficult to accomplish since, at that distance, even a satellite the size of the International Space Station would be less than $3 \mu\text{rad}$ wide.

X. DESIGN EXAMPLE

A. OVERVIEW

This thesis grew out of the 2005 Space Systems Engineering Curriculum Capstone Design Project. Ordinarily, the participants in the project are given a very specific mission which their satellite is to perform. In 2004, for instance, the group was instructed to design a hyper-spectral imaging satellite with certain design and performance criteria. In 2005, rather than a specific mission, the group was given a broad mission area and directed to develop not only a satellite to fulfill the desired role, but also the mission, requirements, and design constraints thereof

The mission of this satellite was to protect a co-orbital High Value Asset from the threat of a direct-ascent Anti-Satellite weapon (ASAT) The LIDAR, as the primary payload, was required to perform the mission of detecting, tracking, and determining the threat posed by detected objects. This chapter will illustrate the design process outlined in this thesis, as applied to that project. It should help to answer any questions remaining about how the design trades covered this far might be resolved in a practical manner.

B. MISSION REQUIREMENTS

The primary mission required the sensor to detect small objects at immense distances, determine position, velocity and acceleration, and determine whether the object detected would pass within the exclusion zone of either the HVA or the sensor satellite itself. The exclusion zone was the projected area through which a direct-ascent ASAT would have to pass in order to hit either target. After analyzing the timeline discussed in the Concept of Operations, the Key Performance Parameters were set as follows:

The sensor must detect a 1 m² object at a maximum range of 1500 km

The sensor must be able to correlate subsequent returns into tracks

The sensor must be able to propagate these tracks to determine the closest point of approach.

This mission was the primary reason LIDAR was selected over radar. The extreme range requires that a large amount of energy be reflected off the target in order to generate a detectable return signal. The inherent directionality of lasers allows a much higher percentage of the energy transmitted to fall on the target than can be accomplished with any reasonably sized radar.

Due to the long range involved, this mission became the primary driver for Laser selection and focal plane sensitivity

C. LASER SELECTION

The primary mission requirement that this sensor be capable of detecting an incoming object at 1500 km quickly narrowed our field of Laser choices to those capable of producing high powered bursts at Pulse Repetition Frequencies (PRFs) ranging from 100 Hz to 1 kHz. With these restrictions, our only choices were a Free Electron Laser (FEL), a Chemical Laser, a Gas Laser or a high-powered Solid-State Laser. The FEL was quickly discarded as an option due to its large size. Chemical Lasers and Gas Lasers both require complex storage, piping and pumping arrangements that would be impractical, to say the least, on a small spacecraft.

Now limited to high-powered Solid-State Lasers, we quickly selected a Diode-Laser pumped Neodymium Ytterbium Aluminum Garnet (Nd-YAG) system. Nd-YAG lasers are widely available from a number of companies in a range of powers, PRFs and control schemes. Their primary output wavelength is at 1064 nm, well within the detection band-gap of silicon, which allows us to use an un-cooled focal plane. The widespread availability and use of Nd-YAG lasers also means that there is a wide selection of optical components optimized for use with this frequency. Additionally, every space-based LIDAR we studied for comparison uses this type of laser.



Figure 25. Typical Nd-YAG Laser Head

Using the LIDAR range equation described in Chapter II and plugging in the telescope aperture size and focal plane detection requirements designed below, we determined that a $12 \mu\text{J}$ signal needed to be reflected from the target at 1500 km in order to produce a detectable return. Assuming 10% reflectivity, this means that the target must be illuminated by $120 \mu\text{J}$ per pulse. Allowing for a $40 \mu\text{rad}$ beam divergence, which requires a 6 cm laser aperture, this translates to a 500 mJ per-pulse laser. Assuming 10% wall plug efficiency and a 1 kW engagement power limit, this allows for a 200 Hz PRF. Obviously, a higher efficiency system or a higher power allocation would allow for higher PRFs.

The high power requirement of the laser when in use, the inherent inefficiency of the laser and the infrequent and unpredictable employment of the system combine to provide a significant challenge to the spacecraft thermal design. To compensate for this problem, each laser is mounted on a 2 kg aluminum heat sink, which is itself mounted directly to the radiator. These heat sinks are capable of storing the excess thermal energy released during an engagement and releasing it slowly over the course of an orbit without upsetting the thermal balance of the rest of the spacecraft.

D. TELESCOPE DESIGN

Telescope selection was driven purely by resolution requirements. As the resolution requirement for the secondary mission was more stringent than that of the primary mission, it became the design driver for the telescope. To achieve 2 cm resolution at 6 km with a wavelength of 1064 nm requires an aperture diameter of 39.58

cm by the Rayleigh criterion. Assuming a 10 μm pixel size, this resolution requires a focal length of 3 m. Both of these requirements are well within the capabilities of almost any reflective-telescope manufacturer.

When making this selection, we were unaware of recent advances in the realm of lightweight optics, so we chose the smallest telescope size that would meet the mission criteria. By the time we found out how little such a telescope would weigh, we were too far along in our spacecraft design to upgrade to a larger telescope. A future designer however, might wish to take advantage of these developments by selecting a larger aperture than resolution requirements demand. This would, of course, allow for better resolution, but, more significantly, it would provide more light-gathering capability for the focal plane, reducing the energy-per-pulse required from the laser. Because the energy received is proportional to the area of the telescope aperture, doubling the diameter of the telescope would quadruple the energy received. Thus, a signal $\frac{1}{4}$ as strong reflected from the target would be detected with the same signal strength. This would allow the use of a laser with $\frac{1}{4}$ the energy-per-pulse we selected, which would allow for four times the PRF with the same input power. Alternatively, the same laser could be used, but with double the beam divergence, allowing four times the area to be searched by each pulse.



Figure 26. Lightweight Telescope by Shafer Corporation

E. FOCAL PLANE DESIGN

In selecting the focal plane for this design, a number of considerations had to be taken into account. The detector had to be able to detect very weak signals, preferably single photons. It needed to be a multi-pixel detector, in order to achieve the desired angular resolution. Each pixel must be able to independently report pulse time of arrival with extreme accuracy, to achieve the necessary range resolution. The focal plane must have a low dark-noise count to reduce false detections. As previously noted, the laser selected operates at a wavelength detectable by silicon-based detectors, which greatly simplifies any potential solution.

After considering a wide number of options, including CCDs, small arrays of individual detectors, photomultipliers, image intensifiers, and various combinations of the above, we selected a One-Megapixel Geiger-Mode Complementary Metal Oxide Semiconductor (CMOS) Active-Pixel Sensor (APS) array.

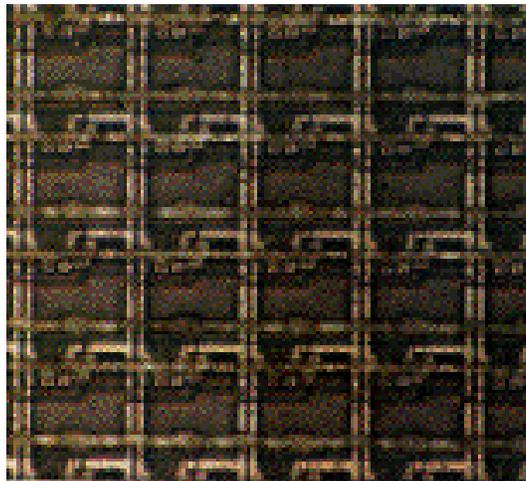


Figure 27. Detail of CMOS-APS array

Geiger-Mode is a method of charging a photodiode above its breakdown voltage such that individual photons register much as clicks on a Geiger-counter. This mode of operation has the dual advantage of being as sensitive as is physically possible while introducing a negligible amount of dark noise. The CMOS APS technology, in addition to being the best-known underlying technology for implementing Geiger-mode

photodiodes in arrays, adds the additional benefits of allowing random-access to any pixel at any time, on-chip analog-to-digital conversion, and on-chip processing of pixel data. By coupling these technologies together, all focal plane design requirements can be fulfilled by a single chip.

F. SENSOR OPERATION

For the primary mission, the satellite is warned of a potentially hostile launch by external sensors. This warning will include the expected intercept track and a volume of uncertainty around the track, assuming the launch is, indeed, an ASAT. With this information, the onboard Command and Control system will predict the time at which the potential ASAT should enter the system's range, and the required search area and pattern to cover the volume of uncertainty. Simultaneously, power will be provided to bring the laser to full operation and to activate the scanning mirror and focal plane. When the computer predicts that the potential ASAT could be entering detection range, the scanning mirror begins to direct the laser pulses into the prescribed search pattern. Any objects within the search volume will return pulses which are then optically resolved onto the focal plane.

Azimuth and Elevation are calculated by noting the position of the illuminated pixel, then performing a coordinate transformation into the reference frame used for predicting possible intercept courses. Range information is determined by correlating pulses detected to pulses sent in the same direction and calculated using time of arrival information. Range gates and non-overlapping consecutive pulse patterns are used to prevent range ambiguity problems.

Once several passes through the search volume have been completed, the processor attempts to develop tracks from separate detections. As these tracks are developed, they are compared to possible intercept courses. Only tracks that represent possible collisions are maintained. As the engagement progresses, the search volume moves, expands and contracts based on actual contacts and predicted position. In other words, if a solid track is developed on a possible collision hazard, the search volume is modified to maintain that track. If no such track is developed, the search volume is modified to continue searching the space around the path that must be followed by any

vehicle traveling from the detected launch area if it is attempting to intercept our spacecraft. Any actual track will be maintained until either impact or miss. Any predicted volume search will continue until any danger of intercept is passed or launch vehicle is determined by other means to be going elsewhere, whichever comes first.

For the secondary mission, procedures are similar, except that they are scheduled well in advance, and the position of the target is reasonably well defined, so the search volumes are much smaller. Instead of using returns to develop tracks, returns are stored and transmitted to the ground to be assembled into 3-D images of the HVA.

G. TECHNICAL CHALLENGES

One of the reasons we were asked to develop this spacecraft was to investigate which areas of technology needed development to effectively operate in this mission area. Below are a few areas requiring further work:

Nd-YAG lasers, while the standard choice for space-based LIDARs, are notoriously unreliable. While some missions, like Clementine, have been spectacularly successful, others, like GLAS, have failed dramatically due to laser burnout. These failures have been attributed to a variety of causes, including insufficient clean room standards, incorrect choice of encapsulated gasses, and the fact that, even today, building a perfect crystal laser is something of a black art. Whatever the reasons, these problems must be solved before a spacecraft like this one can be considered reliable.

One possible solution to this problem may be found in the development of high-power fiber lasers. In addition to being potentially more reliable, fiber lasers are capable of substantially higher efficiencies than Nd-YAG lasers, with some achieving wall-plug efficiencies of 40% or more. Unfortunately, no one is currently making fiber lasers capable of delivering the energy-per-pulse required by this system.

Most significant of the technical challenges is the fact that no one has yet built a focal plane exactly like the one described here as necessary to implement this satellite. Labs have built small Geiger-mode arrays, and there are commercially available multi-

megapixel CMOS-APS arrays, but no one has needed a chip quite like the one we have specified here. Such a chip should be designed, built, and tested before any other work on this satellite commences.

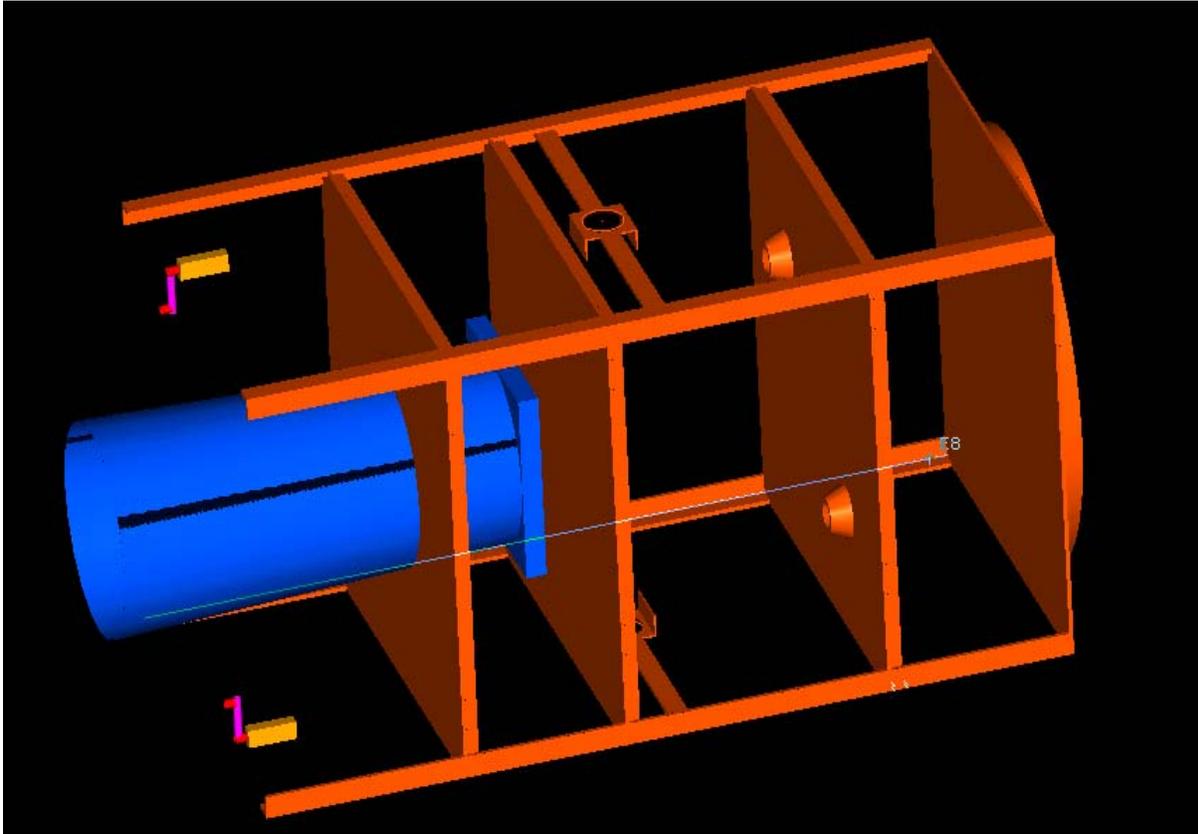


Figure 28. LIDAR System Layout

WORKS CITED

- Abrams, Mark C. and David M. Tratt. "Progress in Laser Sources for Lidar Applications: Laser Sources for 3D Imaging Remote Sensing," Proceedings of SPIE 5653 (2005): 241-248.
- Ahmed, N. and T. Natarajan. Discrete-Time Signals and Systems. Reston, VA: Reston Publishing, 1983.
- Aull, Brian T., et al. "Geiger-Mode Avalanche Photodiodes for Three-Dimensional Imaging," Lincoln Laboratory Journal 13.2 (2002): 335-350.
- Brownlow, L., et al. Instrument Design Tools: Rapid Pre-Phase A Instrument Design Software: EO Cloud/Aerosol LIDAR, Vol 2. El Segundo, CA: The Aerospace Corporation, 2002.
- Carlson, A. Bruce, et al. Communication Systems. Boston: McGraw Hill, 2002.
- Fischer, Robert F., and Bijana Tadic-Galeb. Optical System Design. New York: McGraw-Hill, 2000.
- Gentile, Antinio, et al. "Real-Time Image Processing on a Focal Plane SIMD Array," IPPS/SPDP Workshops (1999):400-405.
- Holst, Gerald C. CCD Arrays, Cameras and Displays. Winter Park, FL: JCD Pub., 1998.
- Janesick, James R. Scientific Charged Coupled Devices. Bellingham, WA: Spie Press, 2001.
- Kuhn, Kelin J. Laser Engineering. Upper Saddle River, NJ: Prentice Hall, 1998.
- Larson, Wiley J. and James R. Wertz, eds. Space Mission Analysis and Design. El Segundo, CA: Microcosm Press, 1999.
- Olsen, R.C. Remote Sensing from Air and Space. Monterey, CA: Naval Postgraduate School, 2003.
- O'Shea, Donald C., W. Russel Callen, and William T. Rhodes. An Introduction to Lasers and Their Applications. Reading, MA: Addison-Wesley, 1977.
- Pedrotti, Frank L. and Leno S. Pedrotti. Introduction to Optics. Englewood Cliffs, NJ: Prentice Hall, 1993.
- Postava, K, et al. "Thickness monitoring of optical filters for DWDM applications," Optics Express 11 (2003): 610-616.

- Reich, R.K., et al. "Low-Light-Level 640X480-pixel CCD Camera for Night Vision Applications." Conference Proceedings, MIT Lincoln Laboratory (1998).
- Rumsfeld, Donald, et al. Report of the Commission to Assess United States National Security Space Management And Organization. Washington DC: GPO, 2001.
- SORCE Interactive Data Access. CU Boulder's Laboratory for Atmospheric and Space Physics. 18 June 2008 <http://lasp.colorado.edu/sorce/sorce_data_access/>.
- Smith Warren J. Modern Optical Engineering. New York: McGraw-Hill, 2000.
- Vallado, David A. Fundamentals of Astrodynamics and Applications. El Segundo, CA: Microcosm Press, 2001.
- Yadid-Pecht, Orly and Ralph Etienne-Cummings, (eds.). CMOS Imagers: From Phototransduction to Image Processing. New York: Springer, 2004.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California
3. Dr. Dan Boger
Naval Postgraduate School
Monterey, California
4. Dr. Brij Agrawal
Naval Postgraduate School
Monterey, California
5. Dr. Chris Olsen
Naval Postgraduate School
Monterey, California