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Synchronous Laser Line Scanners for Undersea Imaging Applications

Fraser Dalgleish, PhD

*Ocean Visibility and Optics Laboratory
Harbor Branch Oceanographic Institute at Florida Atlantic University
Fort Pierce, Florida, USA*

Frank Caimi, PhD., P.E.

*Ocean Visibility and Optics Laboratory
Harbor Branch Oceanographic Institute at Florida Atlantic University
Fort Pierce, Florida, USA*

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16.1 INTRODUCTION

The ability to observe objects underwater has been of great interest historically and many accounts exist in the quest to see “what lies beneath the surface of the sea.” Unfortunately, the physical processes of absorption and scattering from water molecules and suspended particulates hinder the ability to see at great distances, and mandate the use of specialized image formation techniques to extend or even make practical the use of underwater optical imaging systems.

Undersea imaging systems are classified primarily in two categories: *conventional* and *advanced*. Conventional systems utilize either ambient or artificial lighting and a film or video camera. Advanced systems typically require specialized lighting, for example a laser, and some method for eliminating light that is primarily scattered within the medium and not returned from the object of interest in the illuminated field of view. Film cameras, CCD

cameras strobe lights, arc lights, and, more recently, HDTV cameras with LED lighting constitute *conventional* imaging systems. Advanced imaging system architectures have been proposed long before the advent of practical laser systems, and have been implemented using a variety of geometric configurations to mitigate the effects of scattering and absorption.

Conventional camera systems using adjacent broad spectrum light sources for illumination are useful for imaging surfaces at imager to target distances of one to two beam attenuation lengths. An attenuation length is the distance light must travel to be reduced to $1/e$ of its original intensity. It is typically 20 to 30 m in clear oceanic water, and can be less than 1 m in turbid coastal waters. It has been found that at imager to target distances of about three attenuation lengths, acceptable imaging can be provided by spatially separating the light source from the camera, that is, by using a flood light to illuminate the target region. However, as the scattering coefficient increases, the level of common volume scatter increases, and this creates a loss of signal-to-noise ratio (SNR), contrast and resolution ultimately leading to a contrast-limited image.

Advanced imaging systems concepts using laser sources typically provide imaging at distances greater than three attenuation lengths. These extended range imagers are generally of two classes: the synchronous laser line scanner (LLS) class and the laser range gated (LRG) class.

Synchronous LLS is a serial imaging system that provides scanning capability over wide swath (up to 70°) usually with a continuous wave (CW) laser source which is continually tracked on the target over a scan line by a narrow instantaneous field of view (IFOV) single element detector (shown in the left hand side diagram in Figure 16.1) in order to reduce the common scattering volume. Based on results of controlled experimentation and analytical modeling, synchronous scanners have been found capable of operation at maximum distances greater than five attenuation lengths, believed to reach a limit due to shot noise from multiple near-field backscatter in turbid waters, whilst becoming forward scatter limited in clearer water.¹⁻³ Such imagers have been under continued development for use aboard undersea vehicles, including towed bodies, manned submersibles, Autonomous Underwater Vehicles (AUVs) and Remotely Operated Underwater Vehicles (ROVs) to provide imagery for characterizing the sea floor for varied activities including military missions, scientific benthic survey, and inspection of oil and gas infrastructures (Figure 16.1).

Further improvement in imaging range benefits undersea operations by allowing increased vehicle speed and maneuverability and improved image resolution at greater

FIGURE 16.1

Geometric configuration of an underwater laser line scan (LLS) system using synchronous scan method for image formation (a) versus the laser range gated (LRG) system (b).

distances from target regions. The ability to more rapidly and reliably produce higher resolution images of targets and survey sites from greater distances will enable a more extensive and diverse set of applications for underwater vehicles. Depending on the size and complexity of surfaces in the target region, optical sensing may be the only effective means for characterizing features.

By way of example, in the exploration of unknown or dynamic environments, rapid topographical seabed variations can occur at rates greater than the vertical axis performance of the AUV. It is therefore necessary to “fly” the vehicle at a sufficient range above the seabed to avoid potentially catastrophic collisions. Consequently, the design of underwater optical scanning systems must accommodate varying distances to the object plane.

It has also been shown by both simulation and experimentation that the class of laser range-gated (LRG) imagers (shown in the right-hand side diagram of Figure 16.1), that is, those imagers utilizing a pulsed laser source, are also capable of adequate underwater performance for imaging target regions at distances greater than five attenuation lengths, albeit through a narrower total swath than LLS. These systems minimize introduction of energy due to scattered light with divergent laser pulses synchronized with gated intensified cameras.⁴⁻⁷ One advantage of this approach over LLS is that it is not necessary to perform along-track image registration, since the entire FOV is imaged concurrently.

There have also been demonstrated efforts which utilize synchronous scanning with high repetition rate pulsed sources and single element gated detectors.^{2,8} Although these imagers ultimately become limited due to forward scatter between the source and the target, as well as return path attenuation, they can be more compact than CW LLS systems because a spatial offset between the source and receiver is not required to reject scattered light.

Summarily, both classes of extended range underwater imagers are hindered in performance by the point spread and attenuation of the medium, as the laser beam travels from the source to the target region with only a small portion returning to the detector. Scattering and attenuation cause losses in contrast, resolution and SNR. These losses are particularly problematic at and near the range limit of operation.

As a consequence of the requirement to minimize the common scattering volume LLS system designs have a relatively small depth of field (DOF), typically no more than a few meters. This is particularly problematic when imaging in a dynamic undersea environment in which there is significant variation of optical transmission properties, seabed surface features or in which there is significant variation in platform altitude or attitude. Commonly, these factors can lead to unacceptable degradation in image quality or complete signal loss. As shown in Figure 16.2 the DOF is a function of the

FIGURE 16.2

Geometry showing effect of source-receiver separation on DOF and common volume scattering for line scanner architectures.

source–receiver separation distance, the optical path length to and from the target (stand-off distance), beam divergence, and the acceptance angle of the receiver. Figure 16.3 shows how the receiving aperture of the LLS system may be widened to improve DOF. Alternately, a fine adjustment of the optical focus may be slaved in accord with an on-board altimeter.

The optical resolution achievable with a LLS system is dependent on the laser beam diameter at the reflecting surface in the target region, and is also dependent upon the precision with which the receiver can resolve intensity information from the return signal as a function of the scan angle. Minimizing the IFOV, for example, by minimizing the receiver spot size at the target, reduces the scattering volume, which can improve the SNR. That is, the imaging range of the system can be improved by reducing the size of the scattering volume, albeit with a reduction in DOF. This is shown conceptually in Figure 16.3.

Reducing the IFOV reduces the target area per pixel, commonly measured in cm^2 per pixel and, theoretically, improves image resolution. This is particularly desirable when imaging target surfaces having a high spatial frequency, as the combined effects of forward scattering and blurring, due to the limited DOF, further limit the achievable resolution.

The sections that follow describe the optical principles of two different synchronous LLSs. The first system, the concept of which was originally patented in 1973.⁹ has been used since the early 1990s in various packages.^{3,10} The model used in the raytrace analyses in Section 16.3 uses a source–receiver separation of 40 cm. The second system has a smaller source–receiver separation (23 cm) and was developed to bench test alternate system configurations of laser line scan that utilize pulsed and modulated-pulse laser sources which are believed to offer significant potential performance improvements over existing systems. The chapter is organized as follows. Section 16.2 provides a brief historical background to the development of laser line scan underwater imaging apparatus.

Section 16.3 introduces the optical design principals of two alternate types of laser line scan.

Section 16.4 continues a detailed technical discussion by exploring requirements for field-stop apertures in the focal plane to both maintain wide-swath operation and accommodate changes in focal distance.

Section 16.5 presents some recent test tank results generated with one of the featured synchronous line scanners to investigate performance trade-offs with alternate system parameters.

FIGURE 16.3

Geometry showing IFOV effects on common scattering volume reduction, DOF, and image resolution for line scanner architectures.

Section 16.6 concludes with an overview of the main optomechanical desirables for wide-swath extended range undersea laser imaging systems, together with a brief description of future possibilities.

16.2 LLS SCANNING SYSTEM HISTORICAL DEVELOPMENT

Although originally conceived in the early 1970s¹¹ synchronous laser line scan system development began in the 1980s and early 1990s with a series of Navy R&D contracts. Scientists from private contracting firms in the San Diego area were involved in the early phases of development, including Spectrum Engineering Incorporated (SEI). In 1988, SEI began development of the dual pyramidal polygon system designed as an underwater imaging tool, which achieved significant advancements in operational range, field of view, and image quality over conventional imaging systems. During the early 1990s several proof of concept tests were conducted in the field. In tests off San Diego the towed system imaged a sunken WWII torpedo bomber in a “shoot-off” with another laser system known as Wide Area Imaging System (WAIS) as well as several other state-of-the-art intensified camera systems. Commercially oriented tests were also conducted in March 1993 at British Gas Subsea Engineering Centre in Blyth, England in static and towed performance tests in a large test tank in a comparison with SIT, ISIT, and other CCD cameras.¹² The performance of the LSS was clearly superior to the other state-of-the-art imaging systems in this application, and the system was further developed to address a commercial market using an embedded microprocessor control and automated control functions. The commercial system was delivered in October 1992 and was known as the SM 2000. The system was housed in a pressure vessel 80 in long, 11 in in diameter and required 5 kW of power. Over the years it has been used with some success for a variety of habitat survey operations^{10,13,14} and has also been utilized by the Navy for object identification purposes.

Another laser imaging device emerged from Navy contracts into commercial availability at this time. SPARTA, a high technology company with a laser systems laboratory in San Diego developed a range-gated laser imaging device.^{5,6} The system was tested by the Coastal Systems Station in a head-to-head comparison with the LLS system with disappointing results, which may have limited its use by the Navy.³

In 2001, the Office of Naval Research sponsored an assessment of competing electro-optic identification (EOID) sensors.¹⁵ In this assessment, a streak tube imaging lidar (STIL) and two LLS systems were mounted in a tow vehicle along with a suite of environmental sensors. As well as providing the opportunity to assess system performance in challenging environmental conditions, these exercises created a wealth of image data that was useful for performance prediction model validation.

For almost two decades LLS has widely been regarded as the optimal method for acquiring optical identification-quality imagery of the underwater environment. However, there was clearly a need to research performance improvements and to validate modeling and performance prediction software used by the Navy. In 2006 a dedicated underwater LLS test laboratory was built at Harbor Branch Oceanographic Institution (Fort Pierce, FL), now a campus of Florida Atlantic University. A more compact benchtop LLS system was developed in collaboration with Lincoln Laser (Phoenix, AZ), and the details of this system will also be covered in the sections that follow.

16.3 OPTICAL DESIGN PRINCIPALS FOR UNDERWATER LLS IMAGING SYSTEMS

16.3.1 Dual Pyramidal Line Scanner

The first design being considered is based on the original LLS, which, as described in Section 16.2, has been implemented in a cylindrical housing and used on various platforms for a range of seabed imaging tasks. It consists of two pyramidal polygons driven by a single shaft motor, as shown in Figure 16.4.

The laser beam is reflected by each facet of the rotatable polygon toward the target region and a portion of the returning flux is reflected by a second larger rotatable polygon toward the detector, which usually consists of a collection lens, field-stop aperture and a photomultiplier tube (PMT). The two pyramidal mirror assemblies are synchronously coupled along a common axis about which they are each symmetrically aligned. The common axis is coincident with shafts coupling each assembly to a scan motor system that rotates both the assemblies. The pyramidal polygon mirrors have four plane mirror faces or facets which are triangular and which each extends to an apex. As the assembly rotates, the beam incident on a mirror face is reflected at a variable angle that generates a scanning line in space. Thus, for each revolution of the first assembly, four scan cycles are generated, each over a 90° maximum scan angle. The system typically uses the downward 70° of each scan line for imaging.

Reflections created in the target region by the scanning beam form the diffuse portion that is collected from scanning reflections across the rotating faces of the second larger

FIGURE 16.4
Dual pyramidal polygon LLS concept diagram.

pyramidal polygon mirror and condensing optics for input to the PMT. An aperture assembly resides at the focal point of the condenser lens to govern the angular extent of rays entering the PMT. The system of Figure 16.4 may include other common components such as cylindrical correction lenses in order to improve optical throughput.

A necessary characteristic to obtain high contrast images is minimal overlap of the illumination light cone with the receiver IFOV prior to the target plane. Therefore, the receiver must maintain a restricted IFOV, and it is not uncommon to require something substantially less than 5 mrad. In addition, the collection aperture must be large enough to collect sufficient number of photons to extend the range limit of the system. Since the number of photons collected is proportional to the square of the incident aperture diameter, a typical practical aperture may be on the order of 50-mm diameter or more. The mirrors required by the scanner must therefore be relatively large, and contribute to the overall size requirements of the deployed system.

One characteristic of this system is that the curvatures of the output scan field of the transmit polygon and the receive polygon scan field are in the opposite direction. This can require an undesirably large receiver IFOV in order to capture the reflected laser light as it scans across the receive polygon and is reflected back to the PMT. It can also lead to the collected irradiance spot walking over the focal plane of the collection lens and the sensitive area of the PMT, thus requiring a complex aperture assembly and PMT with a large photocathode, respectively.

However, this design is well suited for packaging in cylindrically shaped housings, which are typically tolerant to high ambient pressure and characteristic for some towed bodies and AUVs. In operation, a scan line is developed cross track to the vehicle motion, with the second scan axis being provided by the forward platform motion.

Due to the two-dimensional image being formed through forward motion of the vehicle, the scan rate must be sufficient to scan a large angular field before the vehicle advances too far compared to the along-track resolution requirement Δx . Vehicle maximum speeds, dx/dt are typically several meters per second, so that scan rates of hundreds of lines per second are required. An example calculation for a forward speed of 2 m/s and 1 cm resolution yields:

$$R_{\text{scan}} \approx \frac{dx/dt}{\Delta x} = \frac{2\text{m/s}}{0.01\text{m}} = 200\text{ lines/s} \quad (16.1)$$

For an $n = 4$ faceted mirror, this implies a rotation rate ω according to:

$$\omega = \frac{R_{\text{scan}} \cdot n}{4} = \frac{200 \text{ (lines/s)} \times 60 \text{ (s/min)}}{4} = 3000 \text{ RPM} \quad (16.2)$$

These rates are easily achievable, and clearly, even higher resolution is possible with higher scan rates. It should be noted that for the 70° scan swath utilized with these LLSs, the useful part of the scan duty cycle is 70/90 or 77.6%. A single line scan time τ_L is given by:

$$\tau_L = \frac{\text{Scan Duty Cycle}}{R_{\text{scan}}} = \frac{0.776}{200\text{ lines/s}} = 0.00388 \text{ s} = 3.88 \text{ ms} \quad (16.3)$$

Assuming a cross-track angular resolution δ or IFOV of 2 mrad (0.114 deg) corresponding to the receiver angular aperture, the imaging detector must be able to resolve each pixel in a time given by:

$$t_r = t_L \frac{d}{\text{FOV}} = 3.88 \text{ ms} \frac{0.114 \text{ deg}}{70} = 0.0064 \text{ ms} = 6.4 \mu \quad (16.4)$$

The minimum cross-track number of pixels N is given by:

$$N_{\text{crosstrack}} = \frac{\text{FOV}}{d} = \frac{70}{0.114} = 614 \quad (16.5)$$

However, in practice higher sampling is used to allow for better resolution, and also to facilitate sample integration to improve SNR when necessary.

Typically, the postdetection optics is comprised of a telecentric collection system, where the angular acceptance angle is determined by the focal length of the system and a controllable aperture of diameter d . Ideally, the scanner should allow the collection system to operate with a fixed aperture, implying that the angular deviation of the collected photon bundle be constant regardless of scan angle or distance to the object plane. For a fixed aperture D , the instantaneous angular aperture δ would be given according to:

$$d = \tan^{-1} \frac{d}{2f} \quad (16.6)$$

Assume for example, a scanner exit aperture of $D_{\text{exit}} = 50 \text{ mm}$. A practical lens focal length f of 100 mm, that is an $F\# = 2$, would require an aperture given by:

$$d = 2f \tan d = 200 \text{ mm} \times \tan(0.002 \text{ rad}) = 0.4 \text{ mm} \quad (16.7)$$

However, due to the known scan deviations with this design, the collected irradiance maximum will move with both scan angle and target distance variations. This effect will be examined in Section. 16.4.

16.3.2 Single Hexagonal Polygon Line Scanner

The second design to be considered consists of a single hexagonal polygon, which uses two symmetrical steering mirrors to adjust for changes in target distance (shown in Figure 16.5). It was designed, fabricated, and tested collaboratively between Harbor Branch Oceanographic Institute at Florida Atlantic University (Fort Pierce, FL) and Lincoln Laser (Phoenix, AZ). The broad design requirement was the need for a wide-swath scanner that is compatible with a small active area detector through various target distances.

This scanner system uses a hexagonal shaped polygon and two symmetrical steering mirror assemblies (also shown in Figure 16.9) to synchronize the laser beam transmit path with the return path to the PMT through an entire line scan. When one facet is positioned to direct the laser beam along the transmit path, another facet is positioned to reflect radiation along the detector signal path toward the telecentric collection optics and field-stop aperture which govern the receiver IFOV. The steering mirrors remain symmetrical about

FIGURE 16.5
Single hexagonal polygon LLS concept diagram.

the center of the polygon axis, and only require adjustment to focus at a different target plane. The polygon assembly is coupled to a motor drive system for rotation at steady state speeds in the range of 1000 to 4000 rpm, although higher or lower rotational speeds may be selected based on required performance criteria, within the prevailing environmental and operational conditions. Rotation of the polygon transforms the transmitted beam from a static path into an outgoing scanning path. This rotation simultaneously transforms the static narrow IFOV receiver into a scanning narrow IFOV receiver, synchronized with the laser beam at the target plane through the entire line scan. Lines are scanned through a maximum of 120° from each polygon facet, limited by the length of the steering mirrors to utilize 70° around the nadir. This scan architecture was conceived to substantially reduce the scan deviations inherent in the previously developed systems, making it possible to use a simple aperture and small active area detector.

The outgoing steering optics comprises lower and upper steering mirrors, positioned orthogonally to reflect and thereby direct the scanning portion of the laser beam toward the target plane, as shown in Figure 16.9. The incoming steering optics comprises lower and upper steering mirrors, also positioned orthogonally to reflect and thereby direct the scanning portion of the return path from the same target region toward the polygon facet producing a reflection on a static path toward the PMT.

The prototype was tested with a wedged plane port interface into a test tank thereby limiting the total effective scan angle to be less than 70° . Imaging results using this scanner design are presented in Section 16.4.

16.3.3 Summary

Two alternate wide scan angle line scanner designs have been presented to illustrate different performance characteristics. Both systems have a collection area of approximately 20 cm^2 , corresponding to the area of one polygon facet, to collect enough light for

image formation at extended ranges. The transmit and receive optical paths have been explained for each system up to the collection lens, and the theory by which each design has the potential to achieve synchronous scanning and reflected light collection over a wide total scan angle of up to 70° has been given. A key distinction between the two systems is that the hexagonal polygon system has the ability to adjust the focus distance at the incident aperture of the receiver path via steering mirrors, whereas the pyramidal polygon system uses a more sophisticated aperture assembly at the focal point of the collection optics.

The next section uses results from raytrace simulations of the two designs to examine the distribution of irradiance at the collection lens focal plane through a complete scan line. Furthermore the effect of variations in target distance is also simulated and the required field-stop aperture for each system is determined and discussed.

16.4 RAYTRACE STUDY: FOCAL PLANE APERTURE REQUIREMENTS

The primary optical requirement of both line scanner imagers for use in scattering-dominant waters, is to provide a narrow IFOV which is spatially synchronous at the target plane with the laser beam illumination, over a wide scan angle of up to 70° . This section uses optical raytrace simulation results using Lambda Research TracePro® to examine the spatial characteristics of the irradiance spot at the focal plane of the collection lens. Deviation of the collected irradiance spot due to changes in stand-off distance is also studied to examine the implications of the limited DOF of these designs to realistic environmental conditions. This information is critical to understanding the aperture design of the alternate systems to meet the primary optical requirements. Two key attributes of both scanning designs are analyzed:

1. The position in the focal plane of received light as a function of the scan position
2. The position in the focal plane of received light as a function of the stand-off distance between the imager and the target

Simulated irradiance profiles at the focal plane of the collection lens were produced for five optical scan angles (-35° , -20° , 0° , $+20^\circ$, $+35^\circ$) at three stand-off distances (5.2 m, 7.2 m, and 9.2 m).

16.4.1 Dual Pyramidal Polygon Line Scanner

A model for the dual pyramidal polygon line scanner was created which has a source–receiver path separation of 40 cm to be consistent with the existing systems. To improve ray collection efficiency the target was modeled as the inside surface of a cylinder having a radius of curvature equivalent to the target distance (in this case 7.2 m) centered on the scan output. The collected ray bundles were aligned at the center of the focal plane disk for the 7.2-m stand-off distance case. For the simulated cases at 5.2 m and 9.2 m, the target curvature was changed accordingly.

The model is shown in Figure 16.6 for nadir (0°) case as well as $+35^\circ$. It can be seen that an additional aperture was used prior to the collection lens as a stop for stray light for the purpose of this study. In the implemented system the angular aperture is limited by a field-stop aperture in the focal plane.

A summary of the raytrace results for the dual pyramidal polygon LLS is shown in Figure 16.7.

It can be seen from Figure 16.7 and the composite overlaid images of Figure 16.8 that the collected target irradiance walks across the face of the focal plane disk due to both the scan angle variations (cross-track walk-off of almost 2.5 mm for 5.2 m case, shown in the vertical axes of the plots in Figures 16.7 and 16.8) and changes in target stand-off distance (more than 1.5-mm along-track walk-off between 5.2 m and 9.2 m cases, shown in the horizontal

FIGURE 16.6
Dual pyramidal scanner system modeled with back end optics showing a ray trace scan angle of 0° (left) and 35° (right).

FIGURE 16.7
Dual pyramidal polygon line scanner: ray bundles at focal plane for a variety of scan angles and target distances. 15 plots in total. Each plot represents 5 mm × 5 mm on the focal plane.

FIGURE 16.8

Composite overlaid images showing deviation of collected rays at focal plane over a 70° line scan for dual pyramidal polygon scanner (left: stand-off distance 5.2 m; center: stand-off distance 7.2 m; right: stand-off distance 9.2 m). Each plot represents $5\text{ mm} \times 5\text{ mm}$ on the focal plane.

axes of the plots in Figures 16.7 and 16.8). The design of the system field-stop aperture needs to accommodate these deviations.

16.4.2 Single Hexagonal Polygon Line Scanner

A model for the single hexagonal polygon line scanner was created which has a source–receiver separation of 25 cm to be consistent with the fabricated prototype. Again to improve ray collection efficiency the target was modeled as the inside surface of a cylinder having a radius of curvature equivalent to the target distance (in this case 7.2 m) centered at the polygon center of rotation. For the cases at 5.2 m and 9.2 m the target curvature was changed accordingly. The collected ray bundles were aligned at the center of the focal plane disk for the 7.2-m stand-off distance case, and for the results in Figures 16.10 and 16.11, the steering mirror pair were aligned symmetrically at a focal distance of 7.2 m. The model is shown in Figure 16.9 for nadir case, as well as $+35^\circ$. It can be seen that an additional aperture was used prior to the collection lens to limit the collection angle for the purpose of this study. In the implemented system this function is provided by the pinhole aperture residing at the focal plane.

A summary of the raytrace results for the single hexagonal polygon LLS is shown in Figure 16.10.

It can be seen from Figure 16.10 and the composite overlaid image of Figure 16.11 that the collected target irradiance walks minimally across the face of the focal plane disk due to scan angle variations (cross-axis walk-off of $<0.5\text{ mm}$, shown in the vertical axes of the plots in Figures 16.10 and 16.11) and the changes in target stand-off distance (along-track walk-off $>1\text{ mm}$ between 5.2-m and 9.2-m cases, shown in the horizontal axes of the plots in Figures 16.10 and 11).

However, for the 5.2-m and 9.2-m target distance cases, the offset in the received irradiance can be nulled by refocusing the steering mirror pair at the focal distance. Figure 16.12 shows the effect of making steering mirror adjustments for the 5.2-m and 9.2-m cases; it is clear that the along-track walk-off has virtually been eliminated.

16.4.3 Discussion

Raytrace analysis of the two alternative line scanner designs highlights differences in aperture field-stop design to meet the optical performance requirements. More specifically, the results from the dual pyramidal polygon model indicate several second order requirements to achieve the desired level of performance. These include the need for a synchronous positioning of the aperture that defines the acceptance angle δ . This can be

FIGURE 16.9
Single hexagonal line scanner modeled with back end optics showing a ray trace scan angle of 0° (nadir) and +35°.

FIGURE 16.10
Single hexagonal polygon line scanner: focused ray bundles at focal plane for a variety of scan angles and target distances. 15 plots in total. Each plot represents 5 mm × 5 mm on the focal plane.

seen in Figures 16.7 and 16.8, where the focused ray bundle can be seen to deviate as a function of scan angle. The implemented system mitigates the cross-track deviation by utilizing a spinning aperture that is synchronized with the polygon scan motor to maintain a narrow cross-track IFOV through the entire scan line. To accommodate the along-track walk-off due to changes in stand-off distance, the implemented system also includes a

FIGURE 16.11

Composite overlaid images showing deviation of collected rays at focal plane over a 70° line scan for single hexagonal polygon scanner without refocusing adjustment to symmetrical steering mirrors (left: stand-off distance 5.2 m; center: stand-off distance 7.2 m; right: stand-off distance 9.2 m). Each plot represents $5\text{ mm} \times 5\text{ mm}$ on the focal plane.

FIGURE 16.12

Composite overlaid images showing deviation of collected rays at focal plane over a 70° line scan for single hexagonal polygon scanner with refocusing adjustment to symmetrical steering mirrors (left: stand-off distance 5.2 m; center: stand-off distance 7.2 m; right: stand-off distance 9.2 m).

fixed aperture which can be set with knowledge of the desired upper imaging range and lower imaging range. A short distance behind this aperture assembly resides the photo-detector, which is usually a PMT. The PMT needs to have a photosensitive region large enough to accommodate the two axes of walk-off in the collected irradiance profile, whilst being illuminated by an adequately large spot to avoid space-charge limitations. However, having a profile suited to a cylindrical housing, this class of LLS has major advantages in packaging for at-sea use. It has been used extensively for more than 2 decades and is the only known underwater synchronous scanning imager in operational use.

The results from the single hexagonal polygon model with adjustable steering mirrors have some advantages in reducing the complexity of aperture necessary to meet optical performance requirements. By means of both transmit and receive paths reflecting from a single polygon in alignment with the symmetrical steering mirrors, it provides parallel beam entry and exit axes at a selectable stand-off distance. This permits the use of a static pinhole aperture at the focal plane and allows for a smaller active area PMT placed behind the aperture. The purpose of the system was to experimentally investigate LLS performance trade-offs and to experimentally validate radiative transfer performance prediction models for the LLS class of underwater imager in highly controlled conditions at the Harbor Branch laser test facility. Ongoing use of this scanner involves bench testing future generation LLS system architectures that use pulsed and modulated-pulsed sources with gated PMTs. In general, high-speed PMTs needed for these studies have small photocathodes ($<8\text{ mm}$) so the receive path characteristics make the scanner suitable for such studies.

The next section summarizes some sets of test tank LLS imaging results performed with the single hexagonal polygon scanner to experimentally investigate performance trade-offs in both the choice of system geometrical parameters, and the use of alternate illumination and detection schemes. A description of these experiments, including test hardware details and image quality analysis results are given in Dalgleish et al. (2009).²

16.5 TEST TANK EXPERIMENTAL RESULTS USING SINGLE HEXAGONAL POLYGON LINE SCANNER

Experiments were conducted using the benchtop hexagonal polygon line scanner in the Harbor Branch laser imaging test facility at realistic stand-off distances in a variety of turbidity conditions ranging from very clear conditions to greater than seven attenuation lengths. Data were collected at 7-m stand-off distance (Z) for all imaging configurations presented here. The turbidity of the water in the tank was adjusted by adding a mixture of 50% laboratory grade magnesium hydroxide particles and 50% laboratory grade aluminum hydroxide particles. The resultant beam attenuation coefficient (c) and absorption coefficient (a) at 532 nm were measured with a Wetlabs ac-9 transmissometer. To allow for two-dimensional image formation, along-track motion between scanner and target was generated by mounting the target (1.2 m by 1.0 m dimensions) on a large rotating underwater drum (4 m circumference, 2 m length). Image data was collected with the line scanner configured with a 532-nm diode pumped solid state CW laser (maximum power 3 W) and continuous gain PMT. Using an adjustable pinhole iris as the field-stop aperture, the receiver IFOV was adjusted for each turbidity to vary both the common volume scattering volume and DOF. Image results from these tests, showing the effect of increased IFOV on image contrast are shown in Figure 16.13.

For the next sequence of images presented (shown in Figure 16.14), the line scanner was configured with a pulsed laser source and gated PMT. The laser source was a custom high repetition rate green (532 nm) pulsed laser developed by Q-Peak (Bedford, MA). This solid state amplified master oscillator Q-switched YAG laser produced 7-ns FWHM green pulses at a fixed pulse repetition rate of 357 KHz. The average power entering the water was 1.3 W (4.6- μ J average pulse energy) with pulse-to-pulse energy instability of up to 40%. The pulse-to-pulse timing jitter was typically 10–20 ns. A small portion of the output was sampled by a reference detector and was used as a pulse monitor, both to trigger the receiver gate electronics and for normalization of pulse-to-pulse energy variations in acquired images. Correct alignment was verified, and the turbidity cycling and image acquisition sequence was repeated. System parameters (equal energy per pixel entering the water and far field beam divergence of 2 mrad for each laser) were adjusted to allow for a fair comparison with the CW LLS system images.

Despite obvious laser noise in the pulsed-gated LLS image set, the results in Figure 16.14 demonstrate that a significant contrast improvement is possible with pulsed-gated LLS. This is due to the ability of the gated-PMT to temporally reject the first 40 ns of backscatter from the emitted pulses, which contains no target information. The imaging performance of the CW LLS was limited mainly by multiple backscatter and shot noise generated in the receiver, eventually reaching a complete contrast limit beyond six beam attenuation lengths. The pulsed-gated LLS did not become limited due to multiple backscatter, instead reaching a limit (believed to be primarily due to forward-scattered light overcoming the attenuated direct target signal) beyond seven beam attenuation lengths. This result demonstrates the potential for a greater operational limit as compared to the existing CW LLS configurations. Furthermore, the pulsed-gated LLS does not require a significant source–receiver separation to produce quality images, and hence allows for more compact, simpler optical designs which have the potential to be more immune to changes in operating conditions, and hence more reliable than existing systems. Future advances in pulsed laser source technology should allow for these imagers to be suitably small for modern unmanned underwater platforms such as the man-portable AUVs.

FIGURE 16.13

USAF-1951 white-on-black image sequences collected with CW LLS. Receiver angular aperture (in milliradians) and cZ , the number of attenuation lengths is also shown. Images show significant contrast reduction due to increased receiver angular aperture.

16.6 CONCLUSIONS AND FUTURE POSSIBILITIES

The line scanner designs discussed and analyzed in this chapter were both driven by the main optomechanical requirements for wide-swath extended range underwater viewing systems which are operable at variable stand-off distances. The ability to maintain synchronous tracking between laser beam and detector IFOV at the target plane through the entire scan swath of 70° allows a significant reduction in the common scattering volume between laser and receiver, thus spatially rejecting both forward and back-scattered light. To increase collection of light from the target region, a large collector area is required; each described design typically uses a 20-cm^2 collector area, defined by the area of a polygon facet.

The raytrace analysis of the two line scanner designs highlights differences in the required aperture field stop and consequently the minimum photosensitive region of

FIGURE 16.14

USAF-1951 white-on-black image sequences collected with CW LLS (left column) and pulsed-gated LLS using a 40-ns gate delay (right column). Receiver angular aperture was 15 mrad for both sets of images and cZ , the number of attenuation lengths is shown.

detector needed to meet the optical performance requirements. Perhaps the greatest difference between the two systems relates to dealing with variations in stand-off distance, and the implications at the focal plane where the field-stop aperture resides. The dual pyramidal polygon scanner, a mature system that has been operational for almost 2 decades, accommodates changes in stand-off distance at the focal plane via an adjustable field stop. Exhibiting significant along-track scan deviation, it consequently requires a large photosensitive region for detection. The hexagonal polygon scanner, a prototype system for benchtop experimentation of LLS alternatives, accommodates changes in stand-off distance via the use of symmetrical transmit and receive steering mirrors to direct the collected irradiance with minimal deviation at the focal plane. This results in a system that is compatible with a simple pinhole field stop and small photosensitive region for detection. Results in Section 16.5 describe the use of this benchtop scanner to demonstrate the achievable performance improvement of a pulsed-gated configuration of LLS over the existing CW LLS.

The design of the hexagonal polygon scanner was also motivated by the need to use a high bandwidth photodetector, which generally has small photosensitive regions. This is required for detection of pulsed or CW laser sources that use amplitude modulation, coupled with gating and coherent processing on the recovered waveforms. Such schemes, which are believed to offer measurable performance improvements over systems which use CW laser sources and possibly also over pulsed-gated LLS systems as described herein, have the additional potential for enhanced capabilities such as 3-D imaging and multiple-platform imaging.

Future LLSs for undersea imaging applications need to be even more compact to be compatible with current and future classes of man-portable AUV. The use of pulsed or modulated-pulse laser sources together with gated receiver modules can allow for more compact configuration of the described systems. These future systems may also make use of alternate laser scanning technologies, such as the optical microelectromechanical systems (MEMS) class of devices, which in recent years have been emerging in more diverse applications. These systems may be configurable without the need for precise optical path synchronization, instead using more flexible digital control and synchronization techniques and algorithms.

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