Laser Range Sensors

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ABSTRACT

This paper presents the design aspects of laser range finders and proximity sensors being developed at IRDE for different applications. The principle used in most of the laser range finders is pulse echo or time-of-flight measurement. Optical triangulation is used in proximity sensors while techniques like phase detection and interferometry are employed in instruments for surveying and motion controllers where high accuracy is desired. Most of the laser range finders are designed for ranging non-cooperative targets.

Keywords: Laser range sensors, proximity sensors, optical triangulation, pulsed laser range finders

1. INTRODUCTION

Pulsed laser range finders (LRFs) enable accurate and instantaneous distance measurement of non-cooperative targets from several tens of meters to several tens of kilometers. These work on the echo principle very much like radars in which the time taken to receive the reflected pulse from the target is measured and converted to the range since the velocity of light is constant and known. Laser range finders are highly compact owing to the small emitting apertures required to produce a collimated beam at optical wavelengths.

The LRFs are widely used for surveying, both in civilian and defence applications. Military range finder systems are built to stringent standards for reliable operation in harsh environments and play a vital role in providing target range information for fire control applications. A range capability of 10-20 km with an accuracy of ±5 m is typical for these range finders which may operate at repetition rates ranging from 12 pulses/min to more than 15

pulses/s, depending on the application. IRDE is engaged in the design and development of military laser range finder systems for over four decades. Several systems have been introduced into the Services which include LRF for T-55 tank and MBT *Arjun*, LRF for Arty OP Mk-II (Hand-held LRF) and Integrated Day Night Gap Measuring Device. The design of any laser range finder system involves several critical technologies relating to laser transmitter design, low-level signal detection, signal processing, and design of various optical and electronic subsystems.

The laser transmitter commonly employs a xenon lamp pumped solid-state laser operating in the near-infrared such as the neodymium-doped glass-Nd: silicate (1.06 µm) and Nd:phosphate (1.054 µm), and the highly popular neodymium–doped ytterbium aluminium garnet-Nd:YAG (1.064 µm). Nd:YAG has superior thermal and laser properties which makes it the choice for high repetition rate LRF systems. The design is simpler on account of the robustness of the flash lamp against electrical load and temperature variations

and the limited pumping schemes possible. Flash lamps however consume a large amount of electrical power and produce waste heat that must be removed from the system. They also have associated EMI problems and the need for periodic replacement owing to their limited operational life.

The LRF receiver uses a silicon avalanche photodiode (APD) detector which has a responsivity of nearly 36A/W at 1.06 m. The receiver assembly is boresighted with the laser transmitter to within a fraction of a milliradian (mrad). In a typical two-channel LRF system, the receiver is integrated with an optical sight for aiming the laser. In a three-channel LRF, the transmitter, receiver, and sight are separate. The schematic layout of a typical two-channel LRF is shown in Fig. 1.

2. CALCULATION OF RECEIVED POWER

The power received, P_R (in watt) at the detector is given by the range equation

$$P_R = P_T . e^{-2\alpha R} . A_T . \rho . A_r . T_r / A_B .^. R^2 \qquad (1)$$

where

P_T	Power transmitted (W)
R	Range (m)
α	Atmospheric attenuation (per km)
ρ	Diffuse target reflectivity
A_T	Target area (m²)
A_B	Beam area (m²)
T_r	Receiver transmission
A_r	Receiver area (m²)

The attenuation coefficient, α, due to absorption and scattering by the molecules and particles in the atmosphere can be estimated from the empirical relationship

$$\alpha = (3.91/R_v) (0.55/\lambda)^P$$

where $P = 0.585 (R_v)^{1/3}$, R_v being the specified visibility range which is the distance to which the
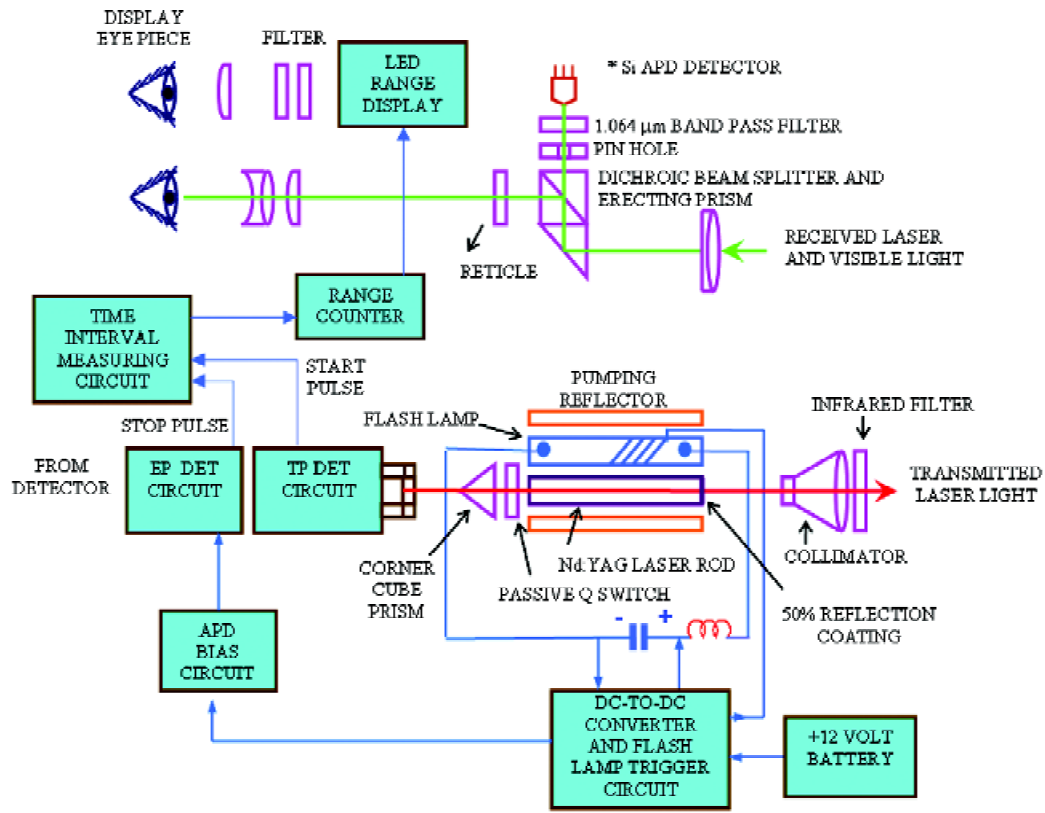

Figure 1. Schematic of a two-channel laser range finders.

eye can discriminate a large target against the background sky. A R_v value of 23.5 km corresponds to good visibility conditions. P_R should have a value higher than that dictated by the system detection level. Knowing P_R, it is easy to calculate either the receiver aperture required for a given transmitted power or the power required for a given receiver aperture from the above expression.

3. SIGNAL-TO-NOISE RATIO

The minimum power required at the receiver for reliable detection depends on the signal-to-noise ratio (SNR). A SNR value of about 5 is desirable in the design. The amplifier signal bandwidth should be 50 MHz or higher to have adequate response to the short laser pulse. For any reasonable value of load resistance the detector will be shot-noise limited. Using a 100 Å bandwidth interference filter with high peak transmission at the laser wavelength, the background radiation can be reduced to a point where it is negligible.

The expression for SNR is given by

$$S/N = \frac{[q\eta.P_R/h\nu]^2.M^2}{B\left[4KT/R_{eq} + 2qM^d\left\{\begin{array}{l}(q\eta.P_R/h\nu)+ \\ (q\eta/h\nu)P_B + I_{dark}\end{array}\right\} + 2qI_x\right]}$$

where

q	Electronic charge $(1.6\times10^{-19}$ C)
η	Quantum efficiency of detector
h	Planck's constant $(6.6\times10^{-34}$ Js)
P	Signal power falling on the detector (W)
B	Band width of the system (Hz)
M	Internal signal multiplication factor for detector
T	Ambient temperature (K)
R_{eq}	Equivalent load resistance (Ω)
d	Multiplication noise constant of the detector
P_B	Background power falling on the detector
I_{dark}	Detector dark current (A)
I_x	Noise current of the amplifier (A)
ν	Frequency of laser radiation (Hz)

4. LASER TRANSMITTER

The laser transmitter should be designed for good optical and mechanical stability. Also it should produce the required peak power for the given application. The laser resonator uses a pair of mirrors aligned parallel to each other and normal to the laser rod axis. One mirror is coated for high reflectivity at the laser wavelength and the other for a reflectivity value between 50-90 per cent depending on the laser medium used. The partial mirror coating is sometimes deposited directly on one end face of the laser rod for simplicity. The other end of the laser rod is anti-reflection coated at the laser wavelength. Laser energy is coupled out through the partial reflector. For enhanced robustness, the high reflectance mirror is sometimes replaced by a corner cube prism which behaves as a retro-reflector (Fig. 1). A crossed porro resonator[5,7] is preferred for environments encountering severe vibrations. This type of resonator uses prisms in place of mirrors with their vertices at right angles to each other. The inherent stability of a single prism in one plane provides a high degree of stability to the resonator. A polarizer and half-wave plate combination is used in the resonator for coupling out the energy via the polarizer.

The laser rod, which is typically 5 mm x 50 mm or 6.25 mm x 75 mm, is pumped closely from one side with a xenon flash lamp having a matching arc length and a gas fill pressure of about 450 torr. A high voltage energy storage capacitor of the metallised polyester film type is connected across the flash lamp and serves to store the required energy of 8-12 joules from a high voltage DC-DC converter. The lamp is triggered by applying a 10-15 KV pulse to it. A pulse forming network comprising of the energy storage capacitor and an air core inductor shapes the current pulse to the flash lamp.

The laser medium when simply excited by a flash lamp or a laser diode within a resonator produces a series of laser pulses of relatively low peak power for the duration of pumping. In order to generate single laser pulses of high peak power from the laser required for range finders, the laser is Q-switched. Q refers to the quality factor of the resonant cavity, a high Q implying low losses. In

the technique of Q switching the cavity Q is initially held low i.e., the cavity losses are made high so that lasing action is prevented and energy is stored in the laser medium during pumping. When a sufficiently high energy has been stored resulting in a large gain, the cavity Q is switched to a high value so that oscillations build up rapidly resulting in the emission of a single giant laser pulse. The time for which the energy may be stored is of the order of the metastable life time of the laser. Q switching is accomplished with some device in the resonator that acts as a fast shutter as illustrated in Fig. 2.

Mechanical devices include the rotating prism in which the rear mirror is replaced with a prism that is mounted on a motor shaft and spun about its vertex at about 20,000 rpm. On every rotation when the prism becomes parallel to the front mirror the cavity losses are minimized. Pumping is initiated when the prism is about 100 μs away from its correct position. When the prism becomes parallel with the front mirror, the energy stored in the laser

medium is released in a single pulse. Being a relatively slow switch this type of Q switching is used with low gain laser materials like Nd:glass and Er:glass.

Electro-optical Q switching uses a lithium niobate crystal to which a quarter-wave retardation[8] voltage is applied. For using this switch the laser has to be first polarized by using a calcite or thin-film polarizer in the resonator. When the polarized light passes through the lithium niobate crystal twice after reflection from the rear mirror, it undergoes 90° rotation and gets rejected by the polarizer. The cavity Q is therefore made low permitting energy to be stored in the laser medium. At the end of the pump cycle the voltage on the crystal is removed instantaneously by means of a high voltage MOSFET or a gas filled krytron switch. The lithium niobate crystal then behaves as a passive optical component with no polarization rotation allowing the laser energy to build up rapidly and be emitted in a single pulse. Since the voltage switching is done by means of electronics the laser pulse emission is highly controlled.
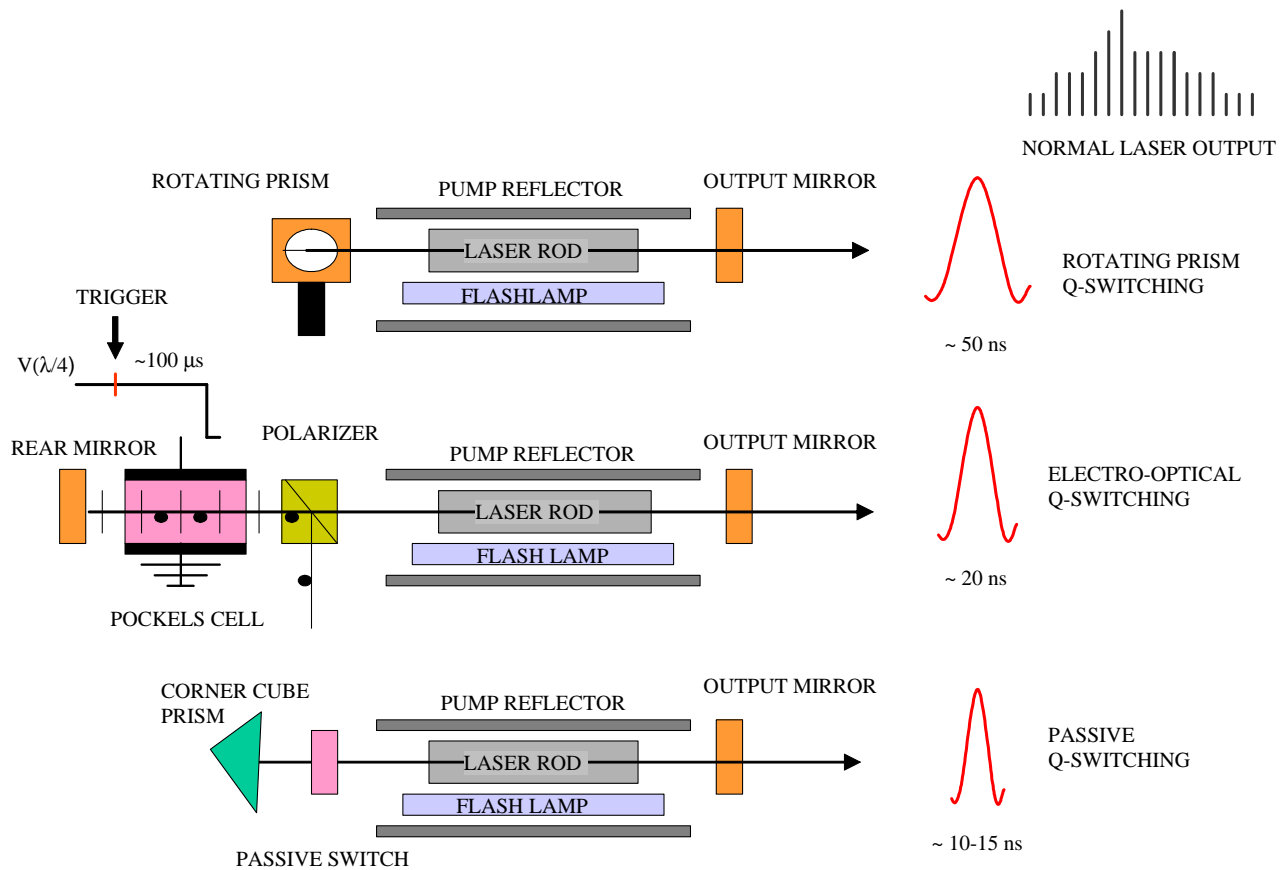

Figure 2. Common Q-switching techniques.

Passive methods of Q switching depend on the property of saturable absorption in certain organic and inorganic materials. These materials when placed in a resonator prevent lasing action and hence aid energy storage by absorbing the cavity radiation. At sufficiently high intra-cavity energy densities, the materials saturate and bleach all of a sudden allowing the laser radiation to build up and be emitted in a single pulse. Passive Q switches include the BDN dye film and chromium ion-doped YAG, also known as black YAG due to its dark appearance. Passive switches are fast and hence can be used with high gain laser materials like Nd: YAG. Passive Q switching is very simple to implement, however the output energy is relatively low on account of the high residual losses of the Q switch in the bleached state.

5. LASER RECEIVER

The laser receiver comprises of a collecting lens of suitable aperture calculated from the range equation, with a *Si* APD detector located at its focus. The detector is reverse biased at a voltage near its break down voltage for maximum sensitivity. As the break down voltage is temperature dependent, the bias voltage needs to be compensated at a rate of about 2.2 V/°C. In practice the bias voltage is made time variable and synchronized in time to the transmitted laser pulse in order to provide a nearly constant receiver sensitivity over the measurement range. Sometimes the amplifier gain is changed with time keeping the temperature compensated bias fixed for the same purpose. The receiver field-of-view (FOV) is kept slightly more than the transmitter beam divergence by proper optical design so as to avoid spurious reflections being received.

The design is carefully optimised to achieve a detection level below 20 nW of incident optical power at the detector, which ensures adequate performance of the laser range finder under varied field conditions. Threshold detection is sometimes used to improve the receiver sensitivity and thereby increase the range performance. The receiver is usually combined with an optical sight by means of a dichroic beam splitter which separates the infrared portion of the spectrum from the visible. A reticle pattern in the sight which is precisely aligned to the laser beam helps in bore-sighting the range finder to the target. An infrared absorbing filter is placed in the sighting channel to provide laser eye-safety to the user. The receiver axis is made parallel to the transmitter axis to within a fraction of a milliradian. A shielded low noise amplifier is used to amplify the detected signal for further processing.

6. RANGE COMPUTING

The target range is given by the relation, $R = ct/2$, where c is the velocity of light and t is the elapsed time between the transmitted laser pulse and the received echo. The time interval unit in the LRF receives electrical start and stop pulses corresponding to the laser pulses being sent and received and in turn generates a time interval pulse. This is used to gate clock pulses from a highly stable clock circuit. The clock frequency is selected to provide the desired range accuracy, 15 MHz for ± 10 m and 30 MHz for ± 5 m. The crystal oscillator is specified to have a temperature stability of approximately ± 10 ppm/°C. The gated clock pulses are sent to a high speed digital counter and the computed range is displayed on a four or five digit LED display in the system. Alternatively, the range information can be sent over a serial data interface to a remote display and control unit or to a computer.

Provision is usually made to range up to two targets in the line of sight simultaneously. Under conditions of poor visibility, false echoes can be received due to atmospheric scattering. A first/last echo logic is implemented for this purpose which allows the user to select either the first or last echoes for range computation. The last echo logic is especially useful for air to ground ranging.

7. LASER SAFETY

Laser range finders pose serious eye hazard during their operation and maintenance resulting from specular or even diffuse reflectance from nearby targets. Lack of awareness or carelessness on the part of the users often compounds the problem. The safe distance for direct viewing of neodymium lasers is usually up to a kilometer or more depending on the beam power and divergence.

Furthermore, if an optical aid is used to view the laser then the minimum safe viewing distance is increased in proportion to its magnification. It is therefore necessary to have an eye-safe laser that poses minimum risk to the user. The laser safety[9] is greatly enhanced if the operating wavelength of the laser is shifted beyond 1.4 μm where it would be effectively absorbed by the ocular media. In a narrow wavelength band centering 1.54 μm, the so called 'eye-safe' band, the maximum permissible exposure (MPE) for direct viewing is about 1 J/cm^2 which is 2×10^6 times greater than at 1.06 μm.

The erbium glass[11] laser operates at 1.54 μm and has therefore been widely used to build eye-safe laser range finders. Erbium glass is however inefficient, and has poor thermal characteristics, which restricts its operation to low repetition rates in flash lamp pumped systems. For high repetition rate eye-safe operation frequency down-conversion of the Nd:YAG laser is the preferred technique and this can be accomplished in several ways. High pressure methane cells employing stimulated Raman scattering (SRS) have been used earlier for this purpose but have now been largely discarded owing to their inherent problems of safety and availability of better methods. Eye-safe Raman conversion has also been demonstrated in molecular barium nitrate crystals and in Nd: KGW laser crystals pumped at 1.3 μm. A more useful method involves phase-matched optical parametric generation (OPG)

in a suitable non-linear crystal such as potassium titanyl phosphate (KTP). In this technique high intensity 1.064 μm pump photons from a Nd: YAG laser are incident on a Y-cut KTP crystal placed in a cavity resonant at 1.54 μm. At pump intensities above the cavity threshold, the crystal generates signal photons at 1.54 μm and corresponding idler photons at 3.44 μm. The idler wavelength is largely absorbed in the crystal and cavity components. The optical parametric oscillator (OPO) converts up to 40 per cent of the incident energy into eye-safe radiation under proper conditions.

8. EMERGING TRENDS (DIODE PUMPED LASER SYSTEMS)

Diode-pumped solid-state lasers are highly efficient because of their excellent spectral overlap leading to almost total absorption of the pump radiation in the laser medium. 808 nm *AlGaAs* laser diodes can be used to pump the Nd:YAG laser, which has peak absorption at this wavelength, with an optical efficiency as high as 40 per cent. Laser diodes themselves have a high electrical efficiency close to 50 per cent which results in a wall plug efficiency of 15 per cent for a Q-switched laser. Also laser diodes operate at low voltages which minimise EMI problems. However the laser diode drive circuitry needs very careful design as they are prone to failure from excessive currents, ESD and electrical transients. The temperature of the laser diodes needs to be
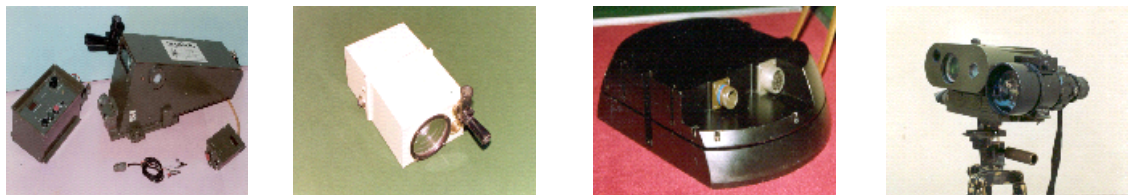
	LRF for T-55 Tank	LRF for Navy	LRD for RPV (Nishant)	LRF for day night gap measuring device
Max. range	4000 m ± 10 m	19995 m ± 5 m	9995 m ± 5 m	999 m ± 1 m
Laser type	Nd:glass (1054 nm)	Nd:YAG (1064 nm)	Nd:YAG (1064 nm)	Nd:YAG (1064 nm)
Q-switch	Rotating prism	Electro-optical	Electro-optical	Passive
PRF	6 PPM	5 Hz	10 Hz	12 PPM
Power/Div	2 MW/ 2 mrad	3 MW / 1.5 mrad	4 MW/ 0.6 mrad	0.1 3 MW/ 2 mrad
Receiver size	40 mm	110 mm	40 mm	40 mm
Detector	*Si* APD	*Si* APD	*Si* APD	*Si* APD
Cooling	Convection	Forced air	Flowing water	Convection
Weight	32 kg	8 kg	7 kg	2.8 kg

Figure 3. Photographs of some IRDE developed LRF systems with specifications.

held at the rated value to within $\pm 1°C$ against ambient fluctuations in order to maintain a constant output wavelength for pumping. This is usually achieved by mounting the laser diodes on a heat sink which is cooled with flowing water or a thermo-electric cooler. Diode-pumped laser technology has been extensively used in scientific and industrial laser systems. A few military laser systems based on this technology are now available in the international market. At IRDE, work is in progress to realize eye-safe diode-pumped laser range finder/designator systems.

Optics design is greatly simplified by the use of aspheric glass components and moulded plastic components in the system. Also miniaturisation of digital electronics has been made possible by the use of programmable logic devices like FPGA and micro-controllers.

The laser ranger designator[12-14] incorporates advanced diode-pumped solid-state laser technology and thermo-electric cooling resulting in a high level of performance and reliability. The Nd: YAG laser-based light weight stand-alone system enables accurate terminal guidance for bombs and missiles fitted with laser seeker. The highly efficient, Peltier-cooled laser transmitter produces 5 MW pulses at 1064 nm with a nominal repetition rate of 20 Hz for designating tank type targets at more than 5 km. The laser receiver uses a silicon APD detector and enables target ranging up to 9995 m with an accuracy of ±5 m. The receiver is integrated with a day sight for accurate engagement of targets.

The system can be configured to operate as a high repetition rate eye-safe laser range finder for aircraft ranging applications by adding an OPO-based wavelength converter module in the transmitter and an InGaAs detector assembly in the receiver. Such systems can supplement air defence radars in the event of their jamming.

9. DIODE LASER RANGE FINDER

A different class of eye-safe time-of-flight LRF can be built using low power *GaAS* laser diodes. Although these operate at 905 nm which is not in the eye-safe band, the power of the laser is kept very low, within the eye-safe limits. A

consequence of this is that the return signal with a diode laser transmitter is very weak with a signal to noise ratio value much below unity. A special signal processing technique involving signal sampling and averaging to enhance the SNR based on the Wild Leitz measurement principle is implemented to extract the signal and determine the range.

In this technique, instead of a single laser pulse a large number of short pulses of laser are emitted, each of which carries only as much energy as allowed by the safety regulations. Each of these pulses is reflected from the target and received by the detector. Due to the low transmitted power, each of the echoes is much weaker than the noise. The random noise can be suppressed by repetitive measurement in which the echo signal accumulates in proportion to the number of independent measurements N, while the noise increases in proportion to $\sqrt{N}$. The term single-shot precision describes the uncertainty limited by random errors in the measurement and it is defined with statistical variance (σ-value) of the distribution, when some constant distance is measured. The precision is calculated from a large enough group of measurement results. The single-shot precision σ_t depends on the slew rate of the incoming pulse and the sum of all squared noise sources:

$$\sigma_{\overline{t}}^2 = \frac{\sigma_n^2}{(dV/dt)^2_{V=D}}$$

where σ_n^2 is the sum of all squared noise voltage sources and $(dV/dt)_{V=D}$ is the slew rate of the input signal. The timing point should be chosen so that the ratio between noise and slew rate is at its smallest. If the single-shot measurements are repeated n times and the oscillators of the transmitter and the time measuring unit are not synchronous (i.e., the single shot measurements are independent of each other), the precision of the averaged result is improved by a factor of N compared to the single-shot precision. In this technique a FPGA-based processor commences the measurement sequence by triggering the laser and starting the ADC. The incoming data are successively stored in a fast memory, thereby creating a wave pattern of time axis. Each memory location stores one sample of
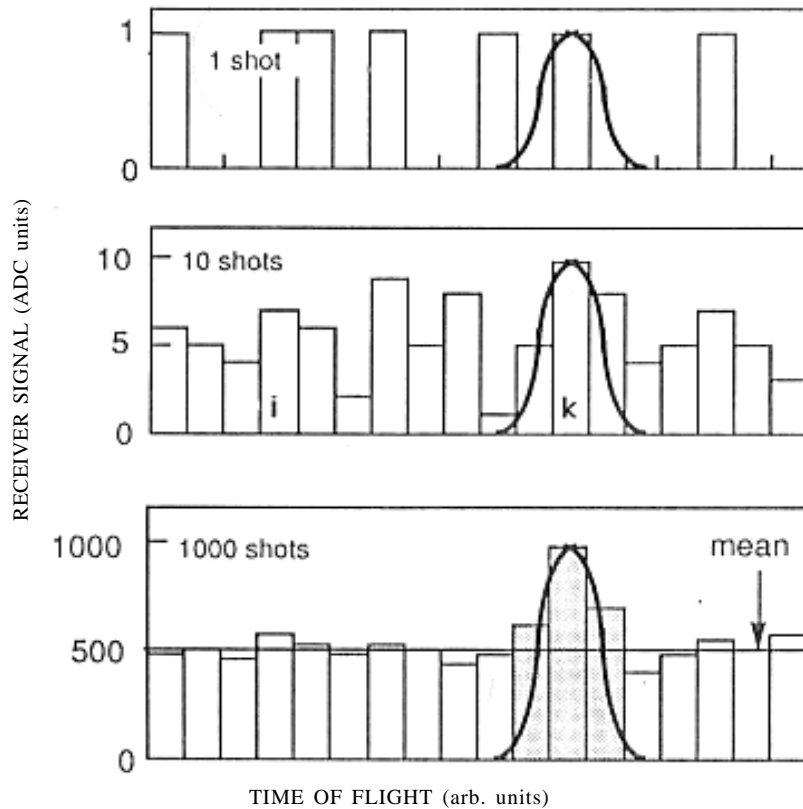
Figure 4. Time-of-flight histogram.

the received signal in a particular time gate. Therefore, for processing the signal a very fast access time memory is required. The final result is displayed on an alphanumeric display with the help of range computing algorithm and accumulating statistics. Diode laser range finders are useful for range measurements up to a kilometer or more on non co-operative targets. Figure 4 is a histogram[10] which shows the received signal in relation to the time-of-flight. As the number of shots is increased and is accumulated, the noise tends to sum up to a level, whereas the signal tends to get sharpened.

10. RANGE PROXIMITY SENSOR

In certain applications as in laser proximity fuzes for warheads it is not important to measure the distance but only to sense the relative position of the sensor with respect to the target. Such a sensor helps to detonate the warhead at a predetermined height from the target ensuring maximum lethality. The principle used for this type of sensor is optical triangulation in which the laser source and receiver built into the range sensor come into field of view at a specific distance from the target surface.

The range of the sensor depends on the angle of projection of the transmitter receiver axes with respect to the mounting base. The accuracy of range sensing depends on the beam divergence (α) of the laser transmitter and the FOV (β) of the receiver optics.

$$H_1 = B[1/\{Cot(\theta-\alpha)+Cot(\theta-\beta)\}-Tan\ \theta/2] \qquad (1)$$

$$H_2 = B[1/\{Cot(\theta+\alpha)+Cot(\theta+\beta)\}-Tan\ \theta/2] \qquad (2)$$

where θ is the base angle and B is the base length

The expressions (1) and (2) enable determination of the divergence of the source and field of view of the detector for different ranges of operation. Comparing the detector output with a threshold reference voltage level can control the working range in addition to preventing false triggering. Safety is further ensured by range gating in which the receiver signal is gated
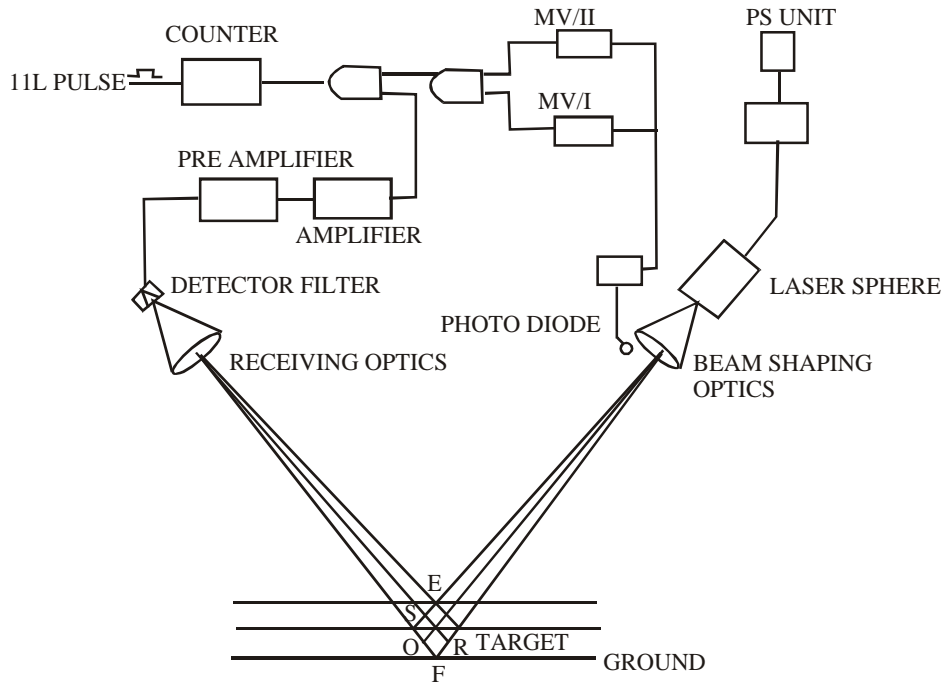
Figure 5. Optical triangulation and range gating technique.

with a pulse synchronised to the transmitted laser pulse. Both the techniques of the proximity fuse are shown in the schematic in Fig. 5

11. CONCLUSIONS

The technology of solid-state LRF for various applications has already been established at IRDE and transferred to public sector undertakings where facilities for production of these instruments have been established. IRDE has also designed and developed a variety of proximity sensors using pulsed semiconductor laser diodes for increasing lethality of bombs and missiles.

A lot of work has also been carried out on signal processing for the detection of low level scattered laser radiation. The technology of flash lamp pumped LRF is presently well matured. However future systems will incorporate diode pumped technology on account of their performance superiority over lamp pumped systems. Recently a prototype of a high repetition rate diode-pumped Nd-YAG laser ranger designator has been developed for missile guidance application. The technology of eye-safe laser ranger finder systems based on optical parametric oscillator has also been established.

REFERENCES

1. Koechner, Walter. Solid state laser engineering, Ed. 5. Springer-Verlag, Berlin, 1999.

2. Silfvast, William T. Laser fundamentals. Cambridge University Press, 2004.

3. Wilson, J. & Hawkens, J.F.B. Optoelectronics: An introduction. Prentice Hall International, 1983.

4. Sovelto, Orazio. Principle of lasers, Ed. 4. Plenum, NewYork, 1998.

5. Chun, M.K. & Teppo, E.A. Laser resonator: An electro-optically Q-switched Porro prism device. *Applied Optics,* August 1976, **15,** 1942-946.

6. Mansharamani, N. Elements of laser ranging techniques. Bishan Singh Mahendra Pal Singh Pub. Co, Dehradun, 2001.

7. Singh, Ikbal; Kumar, Avinash & Nijhawan, O.P. Design of a high power *Nd*:*YAG* Q switched laser cavity. *Applied Physics,* June 1995, **34**.

8. Steel, W.H. Polarisation-preserving retroreflectors. *Applied Optics,* November 1985, **24,** 3433-434.

9. Eye safe lasers components, systems and applications. *SPIE*, 1991, **1419**.

10. Eye safe lasers systems. *SPIE*, 1990, **1207**.

11. Vasan, N.S.; Bahuguna, K.C. & Gaba, S.P. Rotating prism Q-switched Er: Glass laser transmitter. National Laser Symposium (NLS-2000), 13-15 December 2005. LASTEC, Delhi. pp. 89-90.

12. Bahuguna, K.C.; Mishra, Chitra & Vasan, N.S. Diode-pumped eye safe laser transmitter. *In* International Conference on Optics and Opto-electronics, ICOL 2005, 12-15 December 2005, IRDE, Dehradun.

13. Bahuguna, K.C.; Chitra; Vasan, N.S. & Gaba, S.P. Laser diode array pumped transmitter for laser ranger designator. National Laser Symposium (NLS-4), 10-13 January 2005, BARC, Mumbai.

14. Chitra; Bahuguna, K.C.; Vasan, N.S. & Gaba, S.P. Diode pumped high power *Nd*:*YAG* laser system. National Laser Symposium, 5-8 December 2006, RRCAT, Indore.

15. Gaba, S.P.; Vasan, N.S. & Bahuguna, K.C. Erbium-, Ytterbium- and Neodymium-doped glasses for laser application. National Symposium on Science and Technology of Glass/Glass Ceramics (NSGC' 06), BARC, Mumbai, 15-16 September, 2006.