WAVEFORM USE IN INCOHERENT RADAR AND LASER RADAR APPLICATIONS

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1.0 Introduction

It is well established that waveforms of increasing sophistication are indispensible to applied Radar technology [1]. Laser Radar (Ladar) on the other hand has experienced minimal use of such waveform development, despite the fact that the underlying electromagnetic propagation principles are in principle almost identical. There are however large differences in frequency of up to six orders of magnitude, distinct media effects as well as hardware constraints. Some implications for waveform use are mentioned, but the primary focus of this brief study will be to illustrate direct performance advantages of an innovative approach to waveform design, in particular for ***non-coherent*** applications in Ladar, or Radar. Because system complexity is increased to accommodate advanced waveform signal processing, the extra effort and cost must be justified. Though most Radar systems would exhibit unacceptable resolution without waveform use, Ladar systems do not necessarily require them for resolution enhancement, and Ladar sources are typically based on simple compact diode or solid state Q switched lasers. Nevertheless we use a laboratory test setup to demonstrate that the range limit, at equivalent range resolution, can be enhanced in a practical applications, and that this can be applied to non-coherent systems. The tests are not at this stage conducted with an operational system; rather a simulated test setup was used to measure the relative contribution of the waveforms in order to highlight the effects and motivate further investigation. The demonstrated range resolution of 1.5 cm and projected useful range of several km with 1.5 um Ladar transmitters, approaches present state of the art for fielded systems.

2.0 Laser Transmitter Design

A setup for waveform testing was initiated at AFRL Sensors Rome Site to allow interchangeable transmitters, receivers and modulators, The primary laser system transmitter is shown in Figure 1 with the test configuration given in Figure 2.

Erbium Doped Waveguide Laser (EDWL) Transmitter

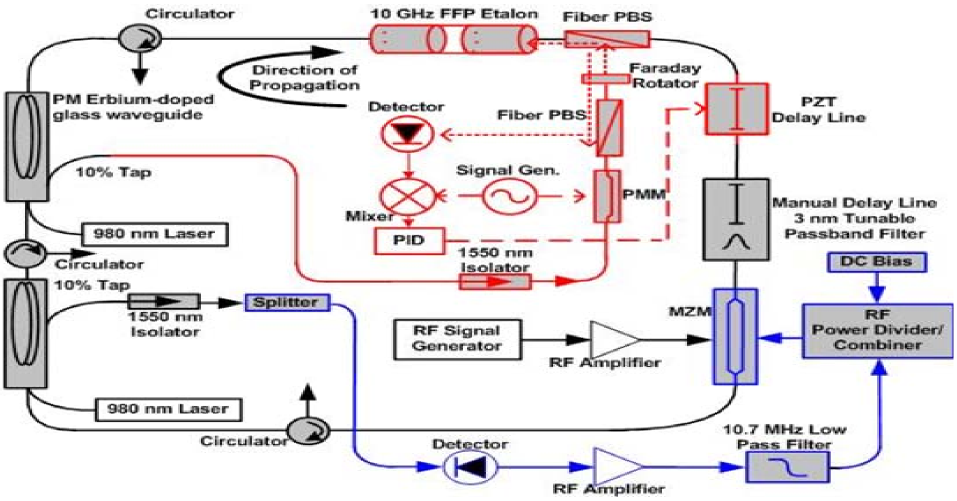


Figure 1

For tests reported here signal processing was non-coherent only, so full stabilization features were not required and in fact the tests also use simpler laser sources, such as a CW Diode laser and a commercial Erbium Doped Fiber Laser (Pritel). This Erbium Doped Waveguide Laser (EDWL) System [2] was developed and then housed in a portable package of dimensions smaller than most commercial Erbium Doped Fiber Lasers (EDFLs). A key advantage over the latter is a gain medium only several cm in length compared with many meters for an EDFL, which greatly simplifies some stability considerations. The advantage over laser diodes is versatility, the EDWL can also generate ultra-short transform limited pulses or operate CW, and appropriate waveform encoding of the laser transmitter with external optical modulation can be done in either mode.

Experimental Setup

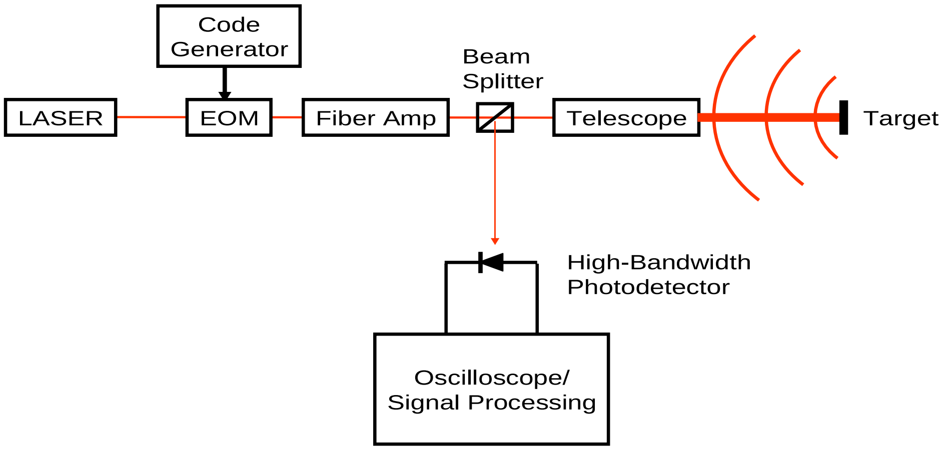


Figure 2

3.0 Test Configuration

The laser transmitter is coupled via single mode optical fiber to a waveguide optical modulator driven by a 12.5 Giga-Bit Pulse Pattern Generator (Anritsu). The signal was amplified with an Erbium Doped Fiber Amplifier (1 Watt) prior to collimation with a 2 inch aperture refractive telescope. The return signal retraces the signal path up to the exit port of the beam splitter leading to high bandwidth detectors (5- 10 GHz). The target made of machined aluminum was located ~ 2 meters distant. This test station was established to compare measured effects in a Ladar simulator with theoretical design projections, at times referred to as *Arbitrary Waveform Generation* (AWG). The terminology should not be taken literally; it is well known that the waveform types of potential interest to Ladar (or Radar) comprise limited and highly specialized subsets of the general case, so that "special purpose waveform generation" would be a more descriptive designation, if required. The most useful types such as pulsed modulation, phase codes, frequency hops, chirps, and orthogonal sets in general require coherent processing. The focus of these tests is in fact further narrowed to *non-coherent* signal processing. Though much less used in current radar because it necessarily precludes parallel Doppler processing, there are in fact applications such as some types of target recognition or imaging in Ladar as well, which do not require Doppler effects, and where practical benefit could be derived by such waveform enhancement.

4.0 Performance Metrics: Coherent & Incoherent

The performance parameter addressed here is *Range Resolution* (not Range Accuracy!). It should be understood that this value is characteristic of a given system, at short range. The performance falls off with increased range because of the sharp decrease in return signal / noise ratio to the point where the signal can no longer be extracted from noise, even with matched filter processing.

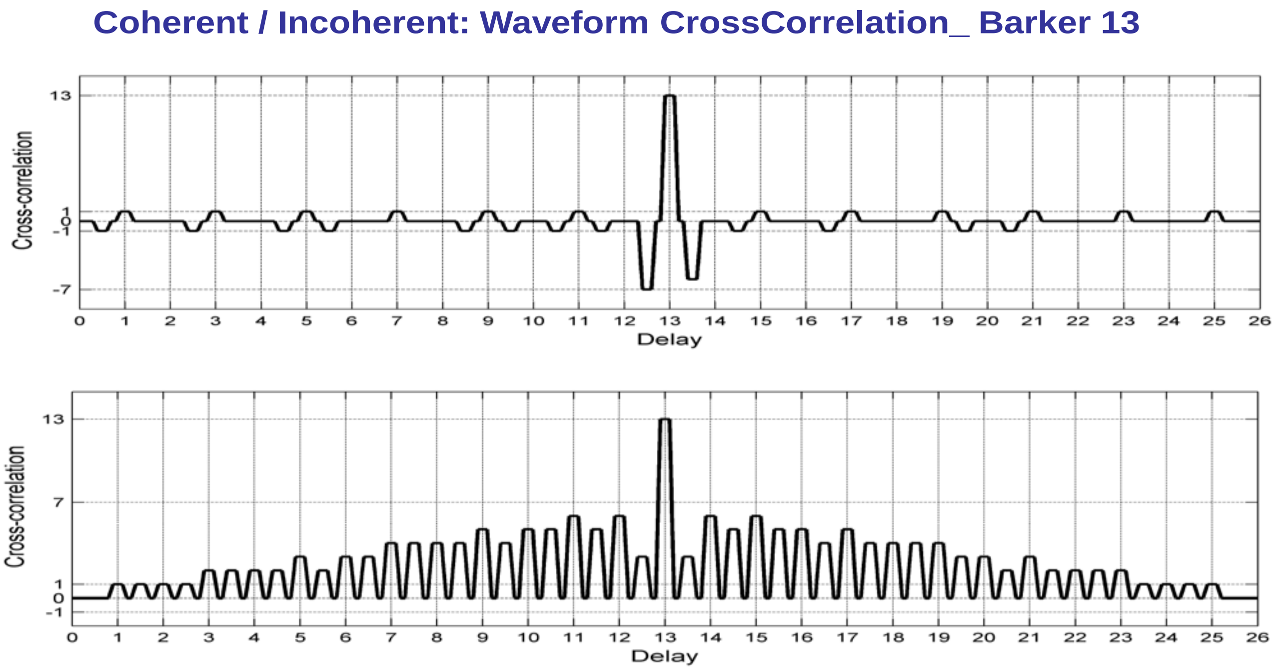


Figure 3

Pulse compression waveforms are essential in Radar where the carrier wavelength itself can be tens of meters, however in Ladar the carrier wavelength is ~ a micron, i.e. ten orders of magnitude less! The practical “chip length” that can be achieved in a binary on-off keying (OOK) format is not actually limited by the wavelength, but by the speed and quality of the signal processing and the energy that can be delivered to a target. The function of the waveform in this case is not necessarily to improve on the (short) range resolution, but to enhance the range limit at which it can be sustained in practice. Waveforms enable that by allowing more energy to be delivered to the target, *without* the sacrifice of resolution which would accompany an increase in the signal pulse duration. Commercial airborne terrain imaging, also with 1550 nm lasers, can achieve 10 cm range resolution, while some stationary interferometric Ladars can exhibit sub mm resolution at short range, also without waveforms. The objective here is to demonstrate resolution approaching the latter value but at practical standoff ranges.

That waveform resolution enhancement's problematic with respect to well resolved correlation peaks in the non-coherent case is illustrated in Figure 3 for the Barker 13 example. The upper plot is the usual coherent cross-correlation wherein the “zero” phase code values are processed as (-1); it displays the characteristic 13:1 S/N ratio. In the lower plot the cross correlation is non-coherent with only positive entries of either 1 or 0, thereby yielding a peak S/N of only ~ 2:1.The sidelobe discrimination is therefore reduced to such an extent that would make spurious signal identification problematic.

4.1 Waveform Designed for Incoherent Application

Trinary Waveform: Tailored for Incoherent Implementation Levenon [ ]

1. **Choose a pulse compression binary sequence. E.g. Barker 13:**
   ***B* = { 1 1 1 1 1 0 0 1 1 0 1 0 1}**

2. **Create a transmitted sequence *T* by applying Manchester coding to *B*. In Manchester coding “1” = 1 0 and “0” = 0 1.**
   ***T* = { 1 0 1 0 1 0 1 0 1 0 0 1 0 1 1 0 1 0 0 1 1 0 0 1 1 0}**

3. **Create a reference sequence *R* in which each 0 of *T* is replaced by -1 .**
   ***R* = { 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1}**

   1. **Replace each chip of *T* and *R* with a narrow pulse of height equal to the chip value preceded and followed by a null (zero) level.**

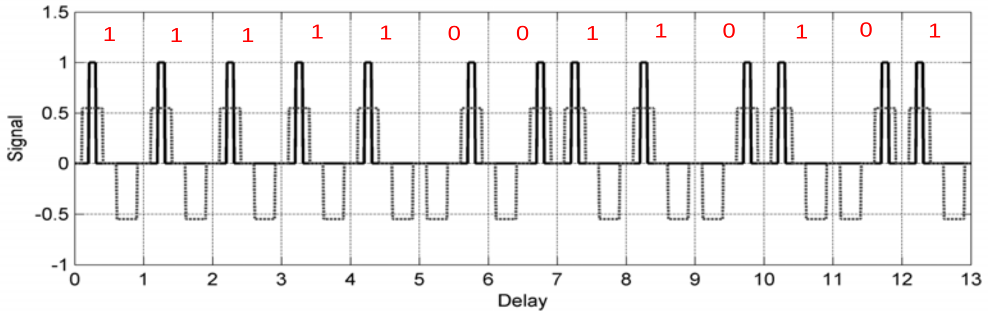


Figure 4

An approach to address this issue with waveform design has been proposed by Nadav Levanon; the calculated simulations yielded very promising results [3], and the tests performed in this work provide the first related experimental measurements. The method involves a ternary modification to the binary reference, as illustrated with Barker code in Figure 4. In Ladar, as opposed to Radar, there are no matched filters available in the receiver hardware to enhance signal discrimination; that function is accomplished by computationally correlating the received signal with a portion of the transmitted reference signal. In the non-coherent case both are positive valued, making a correlation peak almost triangular rather than the sharp peak achieved in the coherent case, The ternary reference addresses this by judicious introduction of negative values in the reference signal; unlike the transmitted signal, the reference signal need not be positive valued. It could in principle come from an independent signal generator with a voltage offset to invert and match the zero levels; but in these tests a single signal generator was used, and a portion of the transmitted signal was detected and stored for reference use. The cross-correlations were carried out in Matlab & Mathcad. It should be emphasized that any performance benefit from these waveforms would apply directly to both non-coherent Radar as well as Ladar.

4.2 Waveform Design Implemented w. 70 Element Code

The waveform that was used was based on what was then the longest known binary version of integer length with peak autocorrelation sidelobe value of 4 [4], whereas Barker 13 has peak sidelobe value of 1. The pulse compression and energy enhancement factors are 70 and 13 respectively [1]. The much greater energy delivered on target for the longer code is highly advantageous in practice to overcome systematic S/N issues entailed in very low return signal levels at or near the effective range limit.

{0110100001001100111011010011100011000010010011111011011101010101111110}

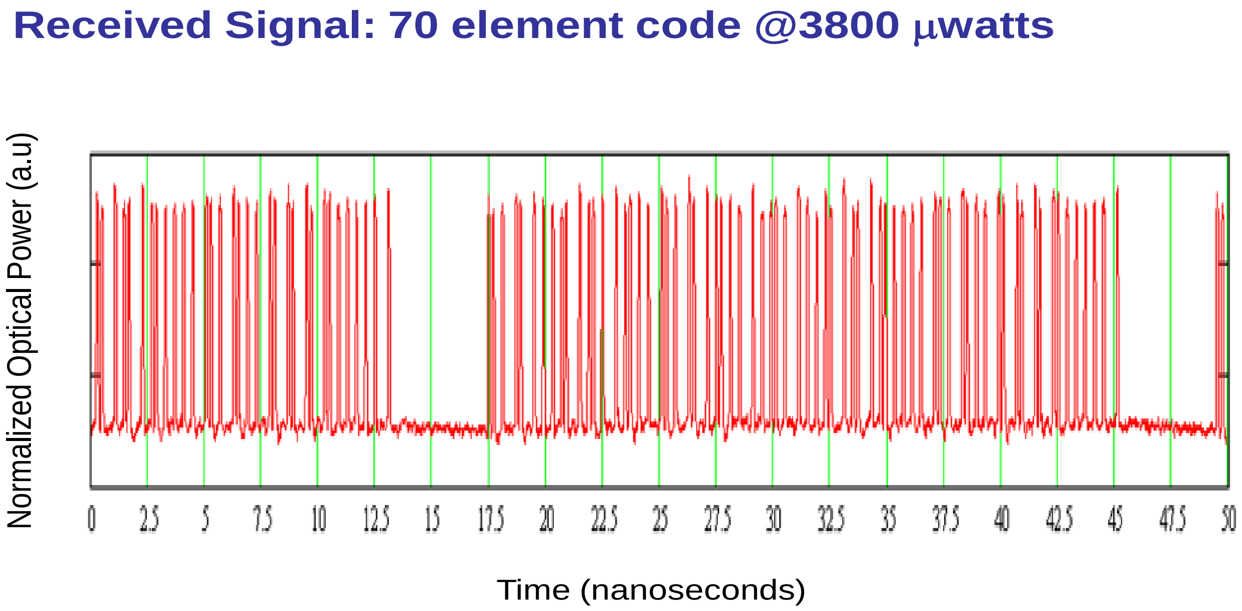
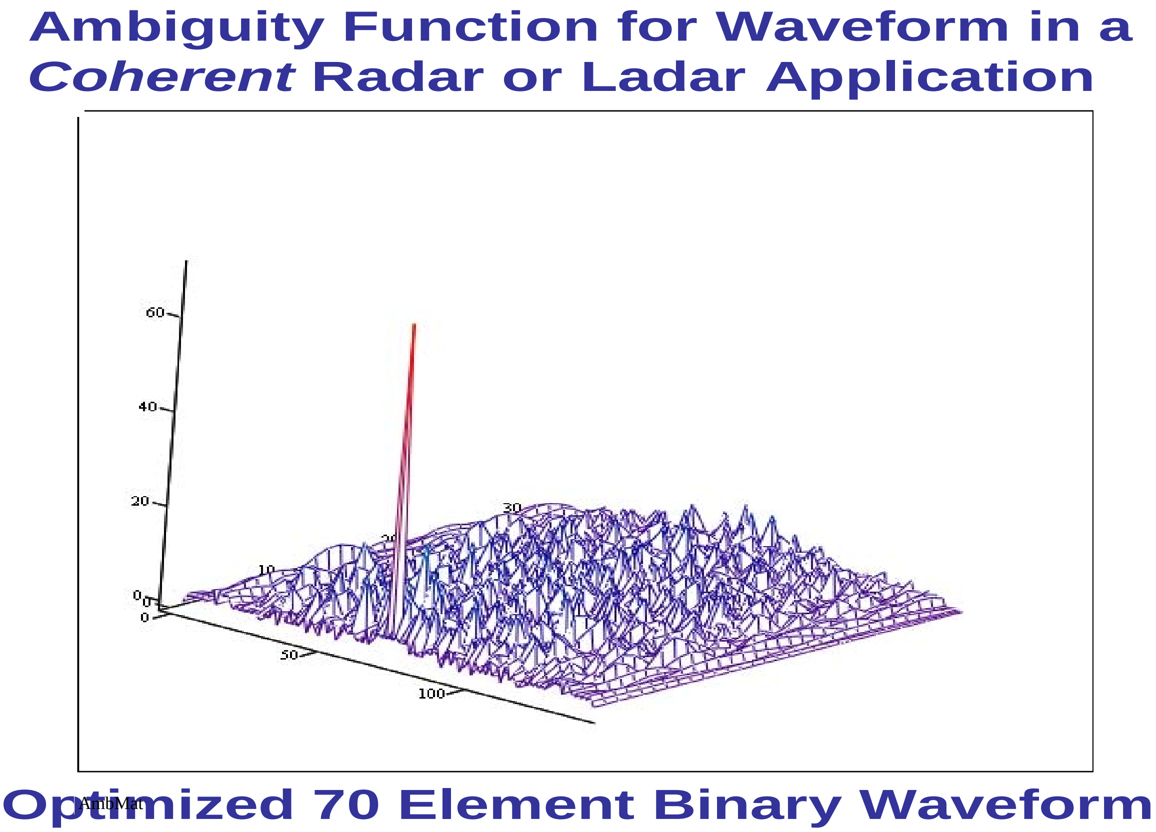


Figure 5

The waveform transmitted and detected in the test setup is shown in Figure 5 with 3.8 mw optical power transmitted. The two volt peak output from the Anritsu Pulse Pattern Generator drove a high speed 20 GHz Optical Modulator (E-Tek Dynamics) with a Vπ value of about 6 volts. The bias voltage was set to the adjusted value which yielded zero transmittance. The modulation signal was offset from the common zero value so that (ideally) the voltage excursion is entirely on one side of the sinusoidal response curve. This results in on-off keying in amplitude, whereas in the coherent case a phase modulator is used. This bias is not in modulator’s linear response region, but for this digital operation this is the proper format.


Ambiguity Function for Waveform in a *Coherent* Radar or Ladar Application

Optimized 70 Element Binary Waveform

Figure 6

The Ambiguity Function serves as a performance metric for the dual basis in range and Doppler coordinate space. The calculated plot (Figure 6) shows that the 70 element waveform has a fairly good “thumbtack like” performance in Doppler resolution as well as range, indicating its multi-purpose potential for either *coherent* Radar or Ladar. For the non-coherent analysis at hand there is no Doppler effect, and the plot slice at zero frequency offset becomes simply the auto correlation of the transmitted waveform, with peak value of 70 and side-lobe limit 4.

4.3 Signal/Noise Enhancement with Waveforms

At the signal power level of 90 uw the returned scatter signal (prior to a matched filter) is on the order of the noise (Figure 7), and serves as a threshold to estimate the relative affectivity of waveforms. The S/N performance can then be compared with that of respective binary and ternary cross-correlations, which are in effect the matched filters for the optical signals. This differs from hardware embedded matched filters in Radar signal processing since the analogous hardware implementation is not available in the optical domain, and must be carried out computationally in the correlations. Similar enhancement of the S/N ratio is expected and observed since 70 X as much signal energy contributes to the data time interval of a ‘single chip’.

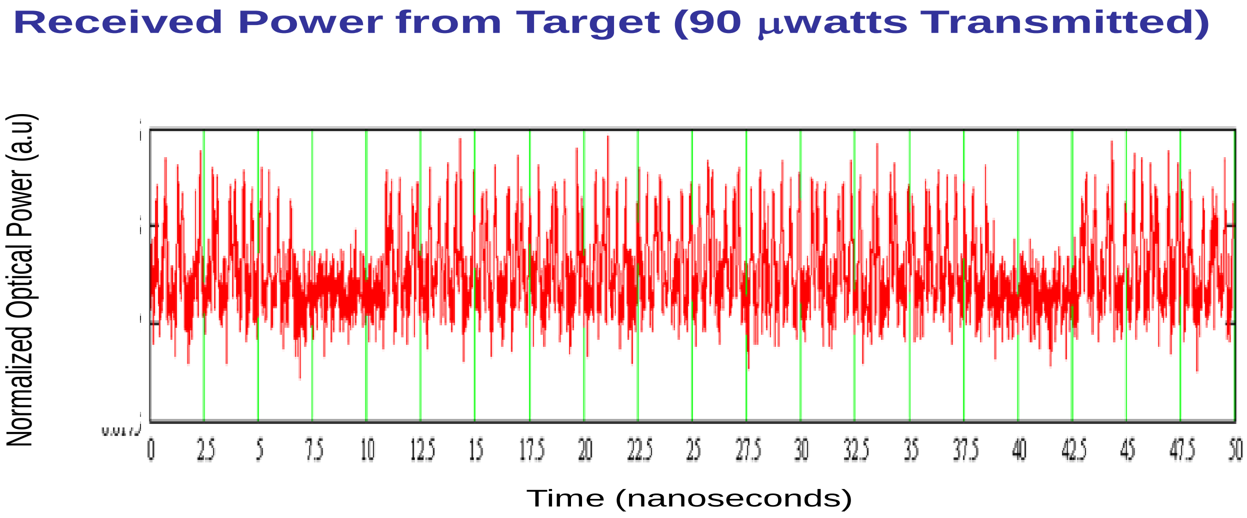


Figure 7

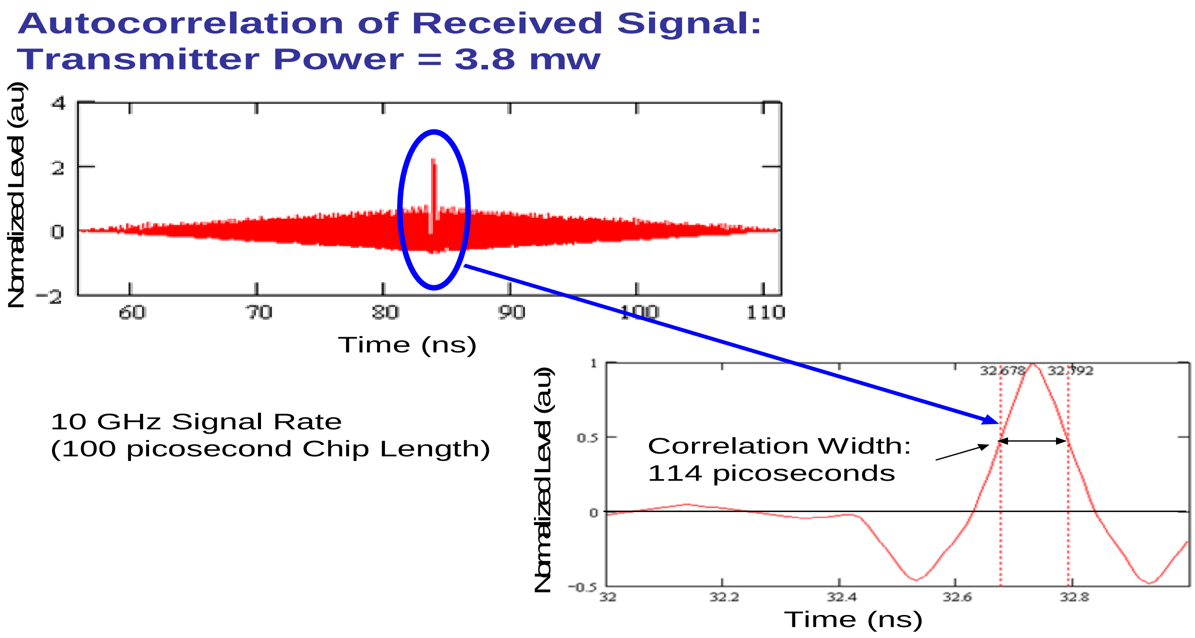


Figure 8

A direct measurement (Figure 8) confirms that the 10 GHz chip length of 100 ps is realized in the return signal. A deviation from the designated value affects the actual range resolution but not the noise, which poses the ultimate range limit for that resolution. It is the waveform shape's deviation from rectangular however which does contribute to the total background noise observed in the figure's top caption; it would also affect the Bit Error Rate (BER) in a related digital communication system. When the same waveform is implemented at a 1 GHz rate (chip length 1 ns) the pulse shapes (not included) are almost perfectly rectangular, with correspondingly lower system noise. The 10 GHz rate was selected to emphasize demonstrate the range performance with state of the art resolution.

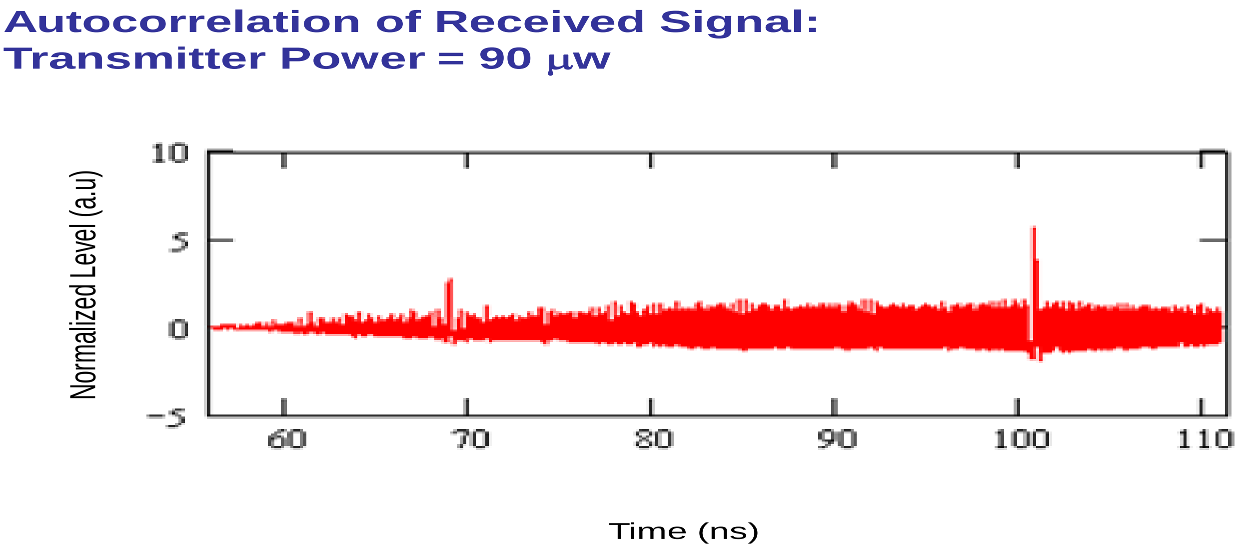


Figure 9

The results in Figure 7 compared with that of Figure 9 at the same threshold power level, show the improvement in signal/noise with only the 70 element waveform. The cross-correlation with the received signal still functions as a ‘partially matched’ filter since it is non-coherently processed with only positive entries. The improvement in S/N to ~ 5:1 is observed. It can be noted that there is a stray scatter peak offset from the primary by about 33 ns (~5 m range). This was not identified at the time of testing, though it was not evident with the superior noise performance of the ternary waveform shown in the following.

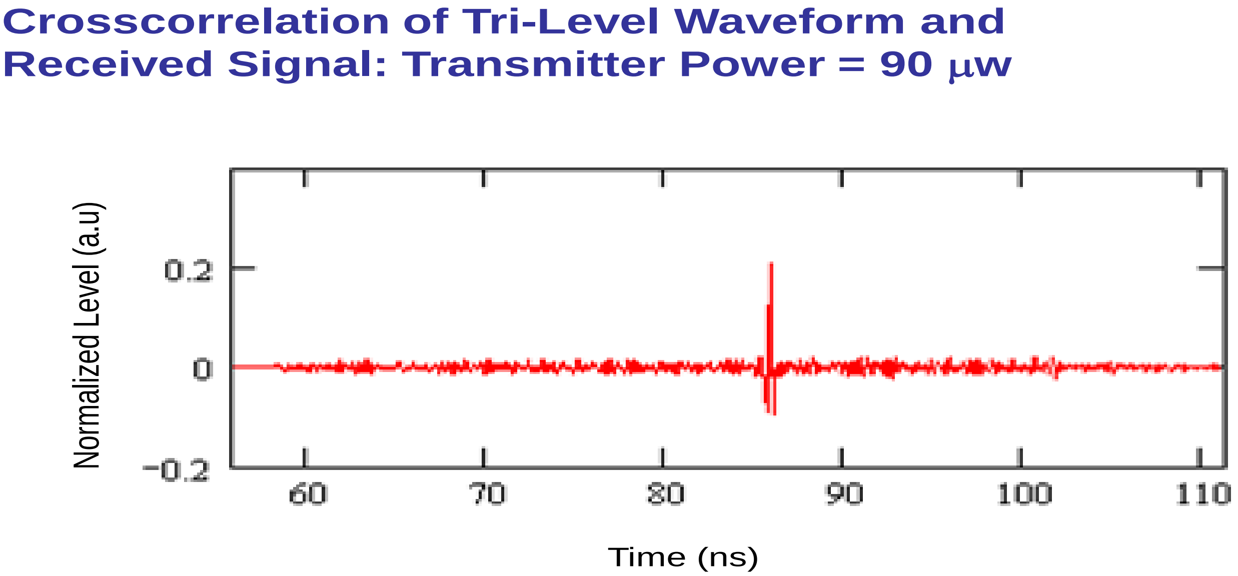
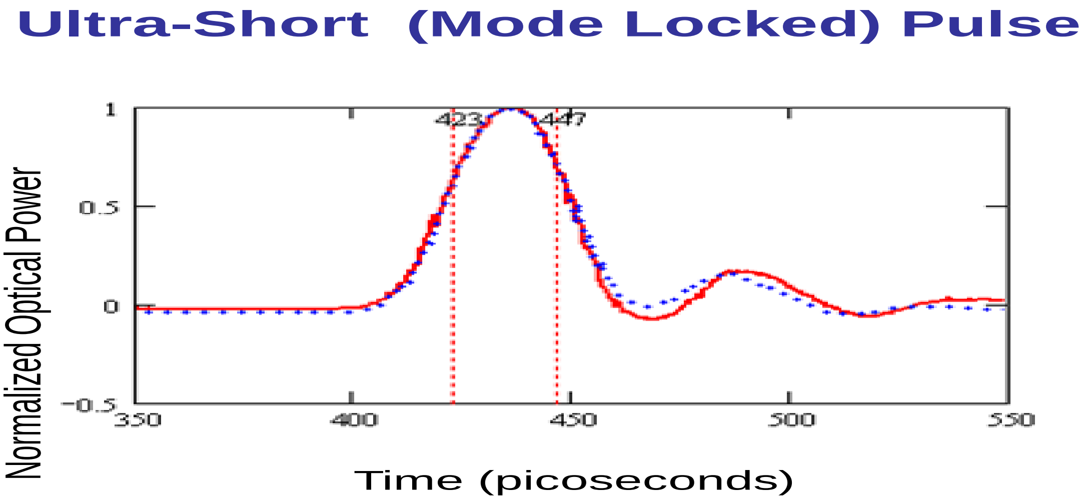


Figure 10

The relevant and meaningful output is plotted in Figure 10. It was obtained by correlating the received signal with the tri-level reference waveform. The correlation sidelobes and noise are substantially lower relative to the autocorrelation of the same 70 element received signal plus noise, shown in Figure 9. The result in Figure 10 is promising for non-coherent application; on board high speed processor chips now enable the computations to be carried out in near real time, making such technology ever more practical where the need justifies the extra system complexity.

5.0 Ultra Short Pulse Operation

When the EDFL laser is harmonically mode-locked, pulses of 10 ps duration are generated at a repetition rate of 10 GHz, which can be synchronized with the pulse pattern generator driven modulator. Waveform encoding can then be superimposed on the ultra-short pulse train, enabling range enhancement to be realized with sub-cm range resolution. The synchronization could not however be established within the time frame of this experimental work. The ultra short pulses were instead characterized in the test system and results were consistent with the expected component limitations. The actual pulse width of 10 ps (established by prior auto-correlation measurement) enables a range resolution of 1.5 mm, but that is realizable in a practical system only to the degree that receiver resolves it. The displayed result in Figure 11 shows the pulse envelope on a 50 GHz oscilloscope display of the high bandwidth detector to yield a ***directly detected*** 23 ps pulse width.



Actual Pulse Width: 10 ps
Detected Pulse Width: 23.2 ps
Detector Bandwidth: 22 GHz

Figure 11

The oscilloscope bandwidth contribution is negligible in this case, thus the practical resolution is detector limited. We also had much higher bandwidth detectors (> 40 GHz) but the necessarily small active area (< 10 um^2) severely limits the accepted light to levels not suitable for km ranges. On the other hand a larger area detector can increase sensitivity and range, but only at the sacrifice of bandwidth and resolution. Both the Thorlabs (SIR5-FC) and the Discovery detectors were based on multimode fiber interfaces, the former with an auxiliary GRIN lens. Both detectors provided the performance tradeoff needed for realizing cm range resolution up to projected km ranges. This ultra short pulse testing of the practical resolution limit provides a prerequisite for further development of high performance Ladar based on it.

6.0 DATA SUMMARY AND EFFECTIVE RANGE PROJECTIONS

	S/N and Range Est @ 90 uw		Range Est @ 5 Watts
Direct Return Signal [70 element binary waveform]	(S/N ~ 1:1)	2 m	90 m
Cross-correlation matched filter [With positive binary reference]	(S/N ~ 5:1)	4.5 m	0.9 km
Cross-correlation matched filter [With ternary reference]	(S/N ~100:1)	100 m	4 km

(Effective range is defined by reaching S/N ratio ~ 1.)

(Effective Range Estimates assume that the laser beam underfills the target, and that the return signal decreases with the inverse square of distance, consistent with a Lambertian scatter model.

7.0 Conclusions:

- Mode-locked fiber and waveguide laser sources can be made sufficiently portable for ground based applications, airborne platforms requires further qualification. Advanced waveforms can also be implemented with CW diode lasers with optical waveguide modulators which are already close to being fielded in airborne platforms.

- Tailored waveforms can significantly enhance the energy delivered to target for incoherent Ladar applications, analogous to sophisticated pulse compression waveform use in coherent Radar.

- A new tri-level waveform design improved the signal-to-noise ratio by almost an order of magnitude over that of straightforward binary matched filtering for incoherent signals.

- Waveform encoding of the signal extended the useful range estimate from ~ 100 meters to ~ 4 km based on the projected use of a fiber amplifier with 5 watt average signal power.

- The range resolution limit demonstrated with 10 GHz modulation of ~ 1.5 cm at short range approaches state-of-the art in deployed systems. The new ternary waveform significantly extended the range at which this could be achieved in any system equipped to implement the waveforms. The actual projections given for useful range and required power serve primarily as comparisons; the key result is performance enhancement, *in the same system*, enabled by tailored waveforms.

- With the EDFL in mode-locked operation, 10 ps pulses were detector resolved at ~ 22 ps to yield a range resolution limit of ~ 3 mm, based on full pulse width detection.

References

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3. N. Levanon and U. Peer: “Non-coherent pulse compression – concept and waveforms”, 21st IEEE Israel AP/MIT & AES Chapters Symposium, Tel Aviv, May 15, 2007

4. G. Coxon and J. Russo, “Efficient exhaustive search for optimal peak sidelobe binary codes” IEEE Trans. on AES Vol. 41, Jan 2005, pp 302-308