Perspectives on the Future of Coherent Ladar

By

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This paper briefly reviews the main benefits of coherent ladar. It then re-caps the history of coherent ladar, followed by a discussion of laser sources for future coherent ladar, future wavelengths, future missions, future waveforms, future optics for coherent ladar, and what benefits of coherent ladar will drive its use,? With coherent ladar you can use poor detectors because a strong LO hides noise, you can measure velocity using Doppler shift, you can directly measure the return field instead of just its intensity. For coherent ladar it is easy to use high duty cycle waveforms, which makes it easy to build efficient laser sources. An initial driver for use of coherent ladar was increased sensitivity using CO_2 lasers. A next driver for coherent ladar was the ability to measure Doppler shift. It is anticipated one of the main drivers for future use of coherent ladar will be its ability to measure field. Among other benefits this will allow coherent ladar using multiple sub - apertures for both transmit and receive, a concept called multiple input, multiple output, MIMO, sensing. Efficient non mechanical beam steering, efficient lasers, and sensitive detector arrays will enable future coherent ladars.

Historical Context:

The historical context of ladar is discussed in ref 1.[1] Coherent wind sensing ladar was started in 1963. There was a first commercial laser Doppler velocimeter instrument about 1969. Beginning in the mid 60's and the early 70's wind sensing research using laser radar became more prominent. Applications included detection of clear air turbulence ahead of an airplane, and detection of wind hazards around an airport. An airport might have an interest both in atmospheric micro bursts over the runways causing strong wind shear, as well as strong wind gradients caused by aircraft wake vortices generated by 'heavy' aircraft.

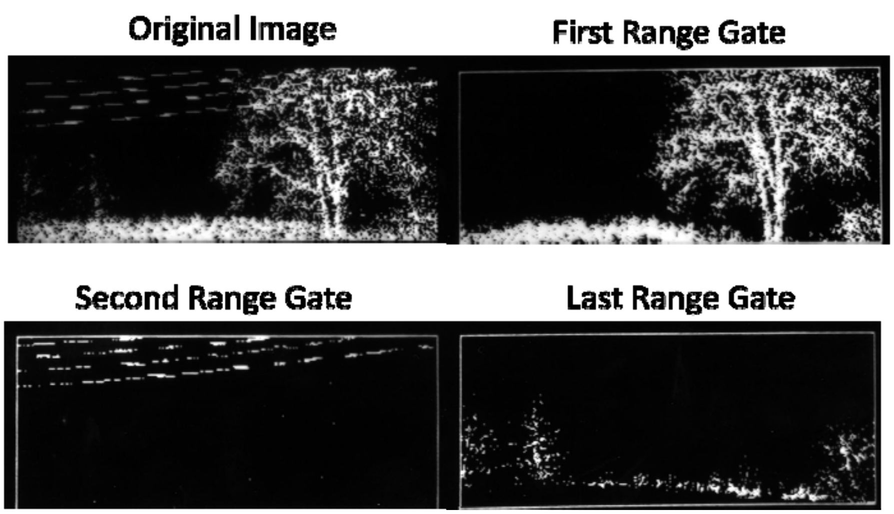


Figure 1: Early 3D laser radar imagery

Figure 1 shows ground test images collected by a short-pulsed, scanned, CO2, heterodyne 3D imaging laser radar about 1983. From 1979 until 1984 there was a program called the Autonomous Terminal Homing, ATH. ATH was a predecessor to the Cruise Missile Advanced Guidance, CMAG, program. The CMAG Program resulted from the need for improved guidance and flight control of autonomous cruise missiles. A cruise missile with this guidance hangs in the Museum of the United States Air Force. CO_2 ladars were also built for terrain following and terrain avoidance, under the Quiet Knight program. MIT/LL did quite a bit of the early work in laser radar. For strategic laser radar a work horse was the MIT/LL Fire Pond system. Firepond used a 20 Watt P22 636 (11.15 µm) master oscillator, mechanically chopped @ 4 to 10 Hz to 35 µsec pulses of 700 µJoules (each). This is an example of CO_2 laser radar that avoided the standard 10.6 µm line, to avoid atmospheric CO_2 absorption. Fire Pond could make range Doppler images. Another application for coherent ladar technology has recently been in the monitoring of winds for wind energy generating platforms. These units are placed on the tower and monitor the wind and turbulence for better operation of the wind power generators. Kinetic in England and Leosphere in France offer these units commercially. The Air Force had interest in wind sensing for air drop, gun ship, and dropping dumb bombs. The flight version of ballistic winds was flown in a near prototype C-130 Pod System June 97. It was 15 cu ft and 1000 lbs. It used a Solid state, 15 mJ, 2 µm laser. In 2002 a Doppler vibrometer was demonstrated over 51 Km., and more recently 3 companies have flown synthetic aperture ladar, SALs.[2]

Perspectives on the Future:

One of the main initial reasons people used coherent ladar instead of direct detection was to mitigate the effects of noise by using a strong LO. For a coherent ladar, the SNR is given by[2]:

$$SNR = \frac{\langle i_s^2 \rangle}{\sigma_n^2} = \frac{\langle i_s^2 \rangle}{\sigma_{ns}^2 + \sigma_{nBK}^2 + \sigma_{nDK}^2 + \sigma_{nTH}^2} = \frac{2\rho_D^2 \eta_{het} P_{LO} P_R}{2eB[\rho_D P_{LO} + \rho_D P_R + \rho_D P_{BK}] + 2eBi_{DK} + 4ktB/R_{TH}}$$

$$= \frac{\eta_D \eta_{het} P_{LO} P_R}{hfB[P_{LO} + P_R + P_{BK}] + KeBi_{DK} + 2KkTB/R_{TH}} \quad (1)$$

where η_{het} is the heterodyne efficiency, which depends on how well the return signal and LO fields are matched on the detector and P_{LO} is the LO power. The rms amplitude of the optical power fluctuations at the difference frequency is $\sqrt{2\eta_{het} P_{LO} P_R}$, which results in a mean squared signal current of $< i_s^2 > = 2\rho_D^2 \eta_{het} P_{LO} P_R$ as seen in the equations. Therefore, the electrical power measured in a heterodyne receiver is linearly proportional to the optical power received. The factor of two is eliminated from the denominator because of the factor of two in the signal times LO power mentioned above. In addition, the LO adds additional shot noise which is accounted for in the denominator with the addition of the P_{LO} term. For coherent ladar the local oscillator power can be increased to dominate other noise sources, assuming the detector dynamic range can handle the local oscillator power. For a well-designed heterodyne case, the main noise will be shot noise from the local oscillator power. The resulting SNR, is given by[2]

$$SNR = \frac{\eta_D \eta_{het} P_R}{hfB}, \quad (2)$$

B is the bandwidth. For the well designed heterodyne receiver (with sufficient LO power), the SNR is proportional to the number of photons received, even when the signal is very weak, whereas, for the direct detection receiver the signal hitting the detector must be strong enough so that its shot (photon) noise dominates all other noise. Recently detectors with high gain have been developed, allowing sensitive direct detection ladar, thus reducing the pull to use coherent ladar for improved sensitivity.

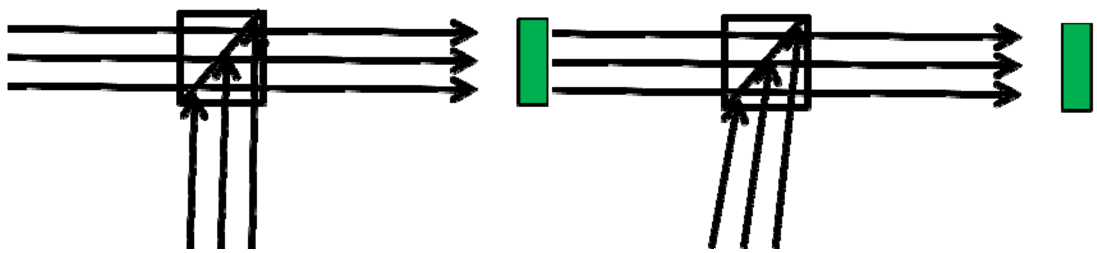
A second benefit of coherent ladar is the ability to directly measure Doppler shift,

$$\Delta f = \frac{2v}{\lambda} \quad (4)$$

Where v is velocity, and λ is wavelength. For optical wavelength we can very precisely measure velocity. A 100 Hz signal would measure a velocity of about 75 µm/sec. for a 1.5 µm wavelength.

A third reason to use coherent ladar is the ease of utilizing high duty cycle, high bandwidth, waveforms. We would like to precisely measure range with a ladar. Short pulses are the easiest method of doing that with direct detection ladar. For coherent ladar we also measure frequency, so we can linearly chirp the frequency, and then compress the signal, to measure range very accurately. This is inherently a high duty cycle waveform. We can also allow frequency, or phase, to jump around pseudo randomly over some bandwidth. This is another high duty cycle waveform. For any laser medium that does not have storage using high duty cycle waveforms means it is easier to make use of cw diodes for pumping.

The last, and in the future the most important, reason to use coherent ladar is the ability to measure the incoming field. We can effectively measure the incoming field either by using a co-aligned LO in conjunction with a high bandwidth detector or by using an angular offset LO in conjunction with a framing camera.



(a) (b)

Figure 2: Temporal (a) and Spatial (b) Heterodyne

In temporal heterodyne usually the LO frequency is offset enough so it is possible to tell which direction an object is moving. This means the LO offset frequency is larger than any Doppler shift of the viewed object. If the LO is not offset in frequency we call this homodyne. In digital holography, which we also call here spatial heterodyne, the LO frequency is the same as the return signal, except possibly for any Doppler shift. Because the LO is offset in angle spatial interference fringes are formed, which allow the experimenter to measure spatial phase variations. Whether temporal or spatial phase are measured this adds knowledge of phase to knowledge of intensity, causing the experimenter to know the captured pupil plane field. Spatial heterodyne has the advantage of being able to use framing detector arrays, so very large FPAs are available. Temporal heterodyne measures piston phase in each detector element. For multiple sub-aperture arrays on receive this additional information makes phasing up the sub-apertures easier.

Once the field is captured we can digitally move between the pupil plane and the image plane using Fourier transforms. We can capture the field in pupil plane, or image plane, or anywhere in between
This means we can in theory do lensless imaging. Sometimes even if we capture the field in the pupil plane we may use optics to expand, or even to compact, the size of the captured pupil plane, if the FPA is not the desired size for capturing the field. We also do need to find a method to provide the LO. Once we have the field you can flip between pupil and image plane using a Fourier transform. We can digitally focus after the fact. We can process (zoom in) on any part of the illuminated area. We can compensate for the atmosphere after field capture using a sharpness metric, or another approach. We can even compensate for extended turbulence. [3] We can synthesize larger virtual aperture. We can coherently combine sub-apertures to form a larger pupil plane array aperture
We can use a moving aperture to synthesize a large aperture.

One of the real benefits of measuring the field is you can then use an array of small apertures to be equivalent to, or better than, a large monolithic aperture. Small apertures with the same F number are much more compact, since their depth is obviously less. Scaling arrays to a large effective aperture size to have better diffraction limited resolution will not cause the optical system to weigh as much as a monolithic aperture. An array of sub-apertures can be much lighter since monolithic aperture weight scales approximately to the 2.7 power of diameter while aperture arrays only scale at close to the 2 power of diameter, by increasing the number of sub-apertures and adding some structure to hold them together. In addition, if transmitter diversity is used as well as receiver diversity it is possible to have the effective aperture almost twice the diameter of the array, provide a further benefit compared to a single large apertures. Lastly using small aperture arrays will allow standardization of smaller sub-apertures that are easy to fabricate rather than building expensive and time consuming large apertures. Figure 3 shows a possible aperture array. Transmit sub-apertures can be common with receive sub-apertures or not. Often however we use flash imaging, illuminating a much larger area than one diffraction limited pixel, so in many situations it might be desirable to use a bi-static strategy with smaller transmit apertures. If we even have a 32 x 32 detector array the

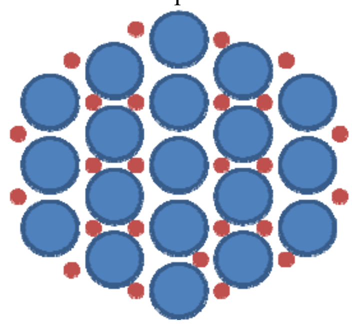


Figure 2, A possible aperture array, with large sub-apertures for receive, smaller sub-apertures for transmit

transmit aperture can be much smaller than the receive aperture. Ladars with arrays such as these are starting to show up in the literature.[4]

It is expected fiber lasers will be the next big transmitter source for coherent ladar. Initially I expect these to be at ~1.5 µm wavelength. Atmospheric attenuation is less at longer wavelengths, especially Raleigh scattering. I expect 2 µm to grow in popularity, followed some ladars in the 3-4 µm region. Of course as you go to longer wavelengths real beam resolution becomes worse, but motion with a synthetic aperture can mitigate than in one direction, and of course bandwidth controls the resolution in the range dimension. Powerful, efficient, and very coherent fiber lasers are becoming available.

At this time while diode lasers are very efficient, and are used as pumps in almost all cases, they are not generally used as the ladar source. With improvement in diode laser spatial and temporal coherence I expect their use will grow.

Detectors are becoming more sensitive, both Geiger mode and linear mode[5]. With the advent of more sensitive detectors the need for a strong local oscillator is less. With advent of larger detector arrays the heating caused by strong Los is more of an issue. As a result I expect LO power levels to decrease for coherent ladar in the future.

While beam steering is required both for direct and coherent ladar it is worth mentioning the development of polarization birefingent beam steering.[6] Each steering element is very thin and can steer to plus of minus a particular angle. Each element has > 99% diffraction efficiency steering to a given angle. Even when building a stack of steering elements to steer too many digital angle efficiency can be kept high. When used with flash imaging we do not need to have a continuous beam steering element, but one can be added if required for a particular design. Figure 3 shows a schematic stack of polarization birefingent gratings.

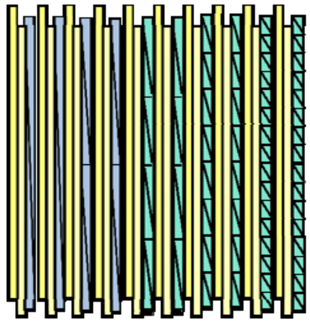


Figure 3: Schematic stack of polarization birefringent gratings.

Summary

The future for coherent ladar is bright. Its use will not be driven by the same drivers that initially caused its popularity in the early Co2 ladar. It will be driven primarily because of its ability to measure phase. This ability will allow unique uses of coherent ladar, especially in array applications. Maturation of laser sources, detectors, and beam steering components will be strong enablers.

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[1] P. F. McManamon, G. Kamerman, M. Huffaker, "A History of Ladar in the United States", Proceedings Vol. 7684, Ladar Technology and Applications XV, Monte D. Turner; Gary W. Kamerman, Editors, 76840T
Date: 4 May 2010

[2] P.F.McManamon, "A Review of Ladar – A Historic, yet Emerging, Sensor Technology with Rich Phenomenology", Optical Engineering 51(6), 060901 (June 2012), p 060901-1 to 060901-13

[3] A. E. Tippie and J. R. Fienup, "Digital Holography with Multiple-Plane Phase-Error Correction," in *Advances in Imaging*, OSA Technical Digest (CD) (Optical Society of America, 2009), paper JTuA5.
http://www.opticsinfobase.org/abstract.cfm?URI=DH-2009-JTuA5

[4] D. J. Rabb et al., "Multi-transmitter aperture synthesis," Opt. Express 18, 24937 (2010).

[5] DOI:10.1080/09500340.2010.547262, M. A. Itzler, X. Jiang, M. Entwistle, K. Slomkowski, A. Tosi, F. Acerbi, F. Zappa & S., Cova, "Advances in InGaAsP-based avalanche diode single photon detectors", p 174-200

[6] J. Kim, C. Oh, M. J. Escuti, L. Hosting, and S. Serati, BWide-angle nonmechanical beam steering using thin liquid crystal polarization gratings,[in Proc. SPIE Adv. Wavefront Contr.: Methods, Devices, Applicat. VI, 2008, vol. 7093