Time of Flight vs. FMCW LiDAR

A Side-by-Side Comparison

FMCWvsTOF_20_0611

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Introduction

Recent papers$^{1–5}$ have presented a number of marketing claims about the benefits of Frequency Modulated Continuous Wave (FMCW) LiDAR systems. As might be expected, there is more to the story than the headlines claim. This white paper examines these claims and offers a technical comparison of Time of Flight (TOF) vs. FMCW LiDAR for each of them. We hope this serves to outline some of the difficult system trade-offs a successful practitioner must overcome, thereby stimulating robust informed discussion, competition, and ultimately, improvement of both TOF and FMCW offerings to advance perception for autonomy.

Competitive Claims

Below is a summary of our views and a side-by-side comparison between TOF vs. FMCW LiDAR claims.

Claim #1: FMCW is a (new) revolutionary technology

This is untrue

Contrary to the recent news articles, FMCW LiDAR has been around for a very long time, with its beginnings stemming from work done at MIT Lincoln Laboratory in the 1960s,[8] only seven years after the laser itself was invented.[9] Many of the lessons we learned about FMCW over the years—while unclassified and public domain—have unfortunately been long forgotten. What *has* changed in recent years is the higher availability of long coherence-length lasers. While this has justifiably rejuvenated interest in the established technology, as it can theoretically provide an extremely high signal gain, there are still several limitations, long ago identified, that must be addressed to make this LiDAR viable for autonomous vehicles. If not addressed, the claim that “new” FMCW will cost-effectively solve the automotive industry’s challenges with both scalable data collection and long-range, small object detections, will prove untrue.

Claim #2: FMCW detects/tracks objects farther, faster

This is unproven

TOF LiDAR systems can offer very fast laser shot rates (several million shots per second in the AEye system), agile scanning, increased return salience, and the ability to apply high density Regions of Interest (ROIs)—giving you a factor of 2x–4x better information from returns versus other systems. By comparison, many low complexity FMCW systems are only capable of shot rates in the 10’s to 100’s of thousands of shots per second (~50x slower). So, in essence, we are comparing nanosecond dwell times and high repetition rates with tens of microsecond dwell times and low repetition rates (per laser/rx pair).

Detection, acquisition (classification), and tracking of objects at long range are all heavily influenced by laser shot rate, because higher laser shot density (in space and/or time) provides more information that allows for faster detection times and better noise filtering. AEye has demonstrated a system that is capable of multi-point detects of low reflectivity: small objects and pedestrians at over 200m, vehicles at 300m, and a class-3 truck at 1km range. This speaks to the ranging capability of TOF technology. Indeed, virtually *all* laser rangefinders use TOF, not FMCW, for distance ranging (e.g., the Voxtel rangefinder[10] products, some with a 10+km detection range). Although recent articles claim that FMCW has superior range, we haven't seen an FMCW system that can match the range of an advanced TOF system.

Claim #3: FMCW measures velocity and range more accurately and efficiently

≠ This is misleading

TOF systems, including AEye's LiDAR, *do* require multiple laser shots to determine target velocity. This might seem like extra overhead when compared to the claims of FMCW with single shots. Much more important, is the understanding that not all velocity measurements are equal. While radial velocity in two cars moving head-on is urgent (one of the reasons a longer range of detection is so desired), so too is lateral velocity as it comprises over 90% of the most dangerous edge cases. Cars running a red light, swerving vehicles, pedestrians stepping into a street, all require lateral velocity for evasive decision making. FMCW cannot measure lateral velocity simultaneously, in one shot, and has no benefit whatsoever in finding lateral velocity over TOF systems.

Consider a car moving between 30 and 40 meters/second (~67 to 89 MPH) detected by a laser shot. If a second laser shot is taken a short period later, say 50us after the first, the target will only have moved ~1.75mm during that interval. To establish a velocity that is statistically significant, the target should have moved at least 2cm, which takes about 500us (while requiring sufficient SNR to interpolate range samples). With that second measurement, a statistically significant range and velocity can be established within a time frame that is negligible compared to a frame rate. With an agile scanner, such as the one AEye has developed, the 500us is not solely dedicated or "captive" to velocity estimation. Instead, many other shots can be fired at targets in the interim. We can use the time wisely to look at other areas/targets before returning to the original target for a high confidence velocity measurement. Whereas, an FMCW system *is* captive for their entire dwell time.

Compounding the captivity time is the additional fact that FMCW often requires a minimum of two laser frequency sweeps (up and down) to form an unambiguous detection, with the down sweep providing information needed to overcome ambiguity arising from the mixing range + Doppler shift. This doubles the dwell time required per shot above and beyond that already described in the previous paragraph. The amount of motion of a target in 10us can be typically only 0.5mm. This level of displacement enters the regime where it is difficult to separate vibration versus real, lineal motion. Again, in the case of lateral velocity, no FMCW system will instantly detect lateral speed at all without multi-position estimates such as those used by TOF systems, but with the additional baggage of long FMCW dwell times.

Lastly, in an extreme TOF example, the AEye system has demonstrated detected objects at 1km. Even if it required two consecutive shots to get velocity on a target at 1km, it's easy to see how that would be superior to a single shot at 100m given a common frame rate of 20Hz and typical vehicle speeds.

Claim #4: FMCW has less interference

Quite the opposite actually!

Spurious reflections arise in both TOF and FMCW systems. These can include retroreflector anomalies like "halos," "shells," first surface reflections (even worse behind windshields), off-axis spatial sidelobes, as well as multipath, and clutter. The key to any good LiDAR is to suppress sidelobes in both the spatial domain (with good optics) and the temporal/waveform domain. TOF and FMCW are comparable in spatial behavior, but where FMCW truly suffers is in the time domain/waveform domain when high contrast targets are present.

Clutter

FMCW relies on window-based sidelobe rejection to address self-interference (clutter) which is far less robust than TOF, which has no sidelobes to begin with. To provide context, a 10us FMCW pulse spreads light radially across 1.5km range. Any objects within this range extent will be caught in the FFT (time) sidelobes. Even a shorter 1us FMCW pulse can be corrupted by high intensity clutter 150m away. The 1st sidelobe of a Rectangular Window FFT is well known to be -13dB, far above the levels needed for a consistently good point cloud. (Unless no object in the shot differs in intensity by any other range point in a shot by more than about 13dB, something that is unlikely in operational road conditions).

Of course, deeper sidelobe taper can be applied, but at the sacrifice of pulse broadening. Furthermore, nonlinearities in the receiver front end (so-called spurious-free dynamic range) will limit the effective overall system sidelobe levels achievable due to: compression and ADC spurs (third order intercepts); phase noise;[6] and atmospheric phase modulation etc., which no amount of window taper can mitigate. Aerospace and defense systems of course can and do overcome such limitations, but we are unaware of any low-cost automotive grade systems capable of the time-instantaneous >100db dynamic range required to sort out long-range small objects from near-range retroreflectors, such as arise in FMCW.

In contrast, a typical Gaussian TOF system, at 2ns pulse duration, has no time-based sidelobes whatsoever beyond the few cm of the pulse duration itself. No amount of dynamic range between small and large offset returns has any effect on the light incident on the photodetector when the small target return is captured. We invite anyone evaluating LiDAR systems to carefully inspect the point cloud quality of TOF vs FMCW under various driving conditions for themselves. The multitude of potential sidelobes in FMCW lead to artifacts that impact not just local range samples, but the entire returned waveform for a given pulse!

First surface (e.g., FMCW behind a windshield or other first surface)

A potentially stronger interference source is a reflection caused by either a windshield or other first surface that is applied to the LiDAR system. Just as the transmit beam is on near continuously, the reflections will be continuous, and very strong, relative to distant objects, representing a similar kind of low frequency component that creates undesirable FFT sidelobes in the transformed data. The result can also be a significant reduction of usable dynamic range. Furthermore, windshields, being multilayer glass under mechanical stress, have complex inhomogeneous polarization. This randomizes the electric field of the signal return on the photodetector surface complicating (decohering) optical mixing.

Lastly, due to the nature of the time domain processing vs frequency domain processing, the handling of multi-echoes—even with high dynamic range—is a straightforward process in TOF systems. Whereas, it requires significant disambiguation in FMCW systems. Multi-echo processing is especially important in dealing with obscurants like smoke, steam, and fog.

Claim #5: FMCW is automotive grade, reliable, and readily scalable

This is unproven at best

FMCW purports to be advantaged by the fact that it leverages photonics and telecommunications technology maturity, thereby facilitating scalability to higher performance levels (in addition to cost savings). True, FMCW allows low cost photodetectors, like PINs, whereas TOF often use APDs and other more costly detectors. However, as we outline below, the details are far more nuanced.

The supply chain for LiDAR components is relatively nascent, but components like Fiber Lasers, PIN array receivers, ADCs and FPGA (ASICS) have been used in various industries for years. These specific types of components are very low risk from a supply base point-of-view. By comparison, the critical component for FMCW systems is the very low phase noise laser, which has many tight requirements and no other high-volume user to help drive down volume manufacturing costs. This is even before the implementation complexities caused by environmental requirements.

The optical components used in TOF LiDAR systems are derivatives of components widely and routinely used in commercial systems (cable TV, telecom, medical instrumentation, and other industries). The new developments are the MEMS, which have also been previously used in virtually all air bag and pressure sensors in automotive, as well as Gatlin guns, missile seekers, and laser resonator q-switches in the military. The components of FMCW systems have been available in laboratory environments for years, but no high-volume production systems have deployed items like the frequency agile long coherence length diode laser needed to enable such systems.

Furthermore, TOF LiDARs already have multiple vendors selling automotive qualified components across the entire hardware stack: lasers, detectors, ASICs, etc. Historically, a disruptive technology (such as FMCW laser sources) that is uniquely manufactured in-house, must have a 10x technical gain to offset a product that enjoys a robust supply chain with multiple vendors already passing quality standards for a given customer base.

Scalability ties directly to maturity. One way of describing technology maturity is a scheme developed by NASA in the 1970s[7] called the "Technology Readiness Level" (TRL). This scheme assigns numbers to a technology according to how far along the path from technology inspiration (TRL 1) to deployment in multiple successful missions (TRL 9). This numbering scheme leaves out the sense of how much work is involved to go from one level to another, but our experience is that there is at least a factor of 10 between each level (and perhaps even a factor of 100).

In the case of TOF LiDAR, we believe the components and systems are at TRL 8, while the FMCW components and systems are at TRL 4. This is a significant gap in technology readiness and will take many years to close. The major scalability shortcomings of FMCW systems include the low shot rate due to the laser chirp pulse stretching, and the high-speed ADC and FPGA required to process returns. In the case where higher shot rates at the system level are required, parallel channels of the optical path and electronics may be deployed. These might use a single scanning MEMS, but each replicated item is most of the cost of the LiDAR system, so doubling channels nearly doubles the overall cost of the LiDAR.

Laser costs

In FMCW systems, coherence length is determined by how the laser is designed and fabricated and must be at least twice as long as the longest target range. Typically, a low phase noise laser is much more expensive than a traditional diode laser. In contrast, outside of maintaining a good pulse shape, there are few other requirements on the laser in a TOF system beyond those already required in telecom markets.

Receiver costs

While it is true that FMCW detectors can be low grade PINs and relatively cheap, the total receiver cost is expensive due to the front end optics and back end electronics requirements. Even here though, a coaxial FMCW system and a coaxial TOF system will not see significant differences in detector costs based on detector sizes needed. The total receiver cost will favor a TOF system.

Optics costs

In a typical TOF system, incoherent detection (simple amplitude peak detection) takes place and optical elements only have to be within one-quarter of a wavelength (so called $\lambda/4$). In comparison, FMCW uses coherent detection and in aggregate, all of the optical surfaces have to be within a much tighter tolerance, like $\lambda/20$. These components can be very expensive and there are much fewer suppliers capable of making them.

Electronics costs

In the AEye TOF system, the electronics consists of a high-speed Analog to Digital converter (ADC) and a Field Programmable Gate Array (FPGA) that performs peak detection and range calculations. The bandwidth of the electronics is proportional to the range resolution and for common LiDAR system requirements, the components are nothing unusual.

FMCW requires ADC conversion rates that are two- to four-times as high as a TOF system and then must be followed by an FPGA capable of taking the data in and doing very high speed FFT conversions. Even with the use of ASICs, the complexity of FMCW systems is several times the complexity (and cost) of the processing required for TOF.

Claim #6: Adding FMCW to Optical Phased Arrays (OPAs) will compensate for lack of solid-state performance of FMCW

? This is unproven

FMCW has a low technical readiness level, and Optical Phased Arrays have an even lower technical readiness level (roughly TRL 3 with experimental proof of principle and is not usable at scale to the extent needed for FMCW). The original DARPA Modular Optical Aperture Building Blocks (MOABB) program demonstrated that, to achieve very low spatial sidelobe transmit beam-steering performance, submicron ($\lambda/2$) waveguides were necessary.[11] The consequence of needing such small waveguides is the power handling capability of such elements, which was identified as a fundamental limitation to the approach. On the receive side, the idea of coupling light from an input lens to a photonic substrate where the light has to be collected into a very small waveguide is also an optical performance challenge (etendue limitation).

Most OPA systems use thermal shifting of laser wavelength to steer beams in one dimension while using phased arrays to steer beams in another dimension. It is well known that phased array beam steering degrades (creates spatial sidelobes) very quickly with frequency shifts of the laser beam. The combination of a beam steering mechanism that depends on the laser being a constant intensity and constant wavelength, while the ranging mechanism depends on sweeping the frequency (wavelength) of the laser, doesn't work well for traditional FMCW approaches. The idea of combining FMCW with this beam steering technology that is in such an early stage of development is incredibly risky. We believe this path can take another 10 years to reach usable maturity.

Conclusion

AEye believes that high shot-rate, agile-scanning TOF systems serve the needs of autonomous vehicle LiDAR more effectively than FMCW when cost, range, performance, and point cloud quality are important. However, it is not hard to see the logical reasoning where FMCW could play a niche role in applications where lower shot rates are suitable and FMCW systems are more economical. While there will be nice videos of FMCW and other low TRL systems in well controlled environments with expensive prototypes, it's a whole different world when taking harsh environments and mass production into account. We hope this white paper will stimulate development and awareness in both TOF and FMCW systems, increasing the component options for perception engineers everywhere.

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