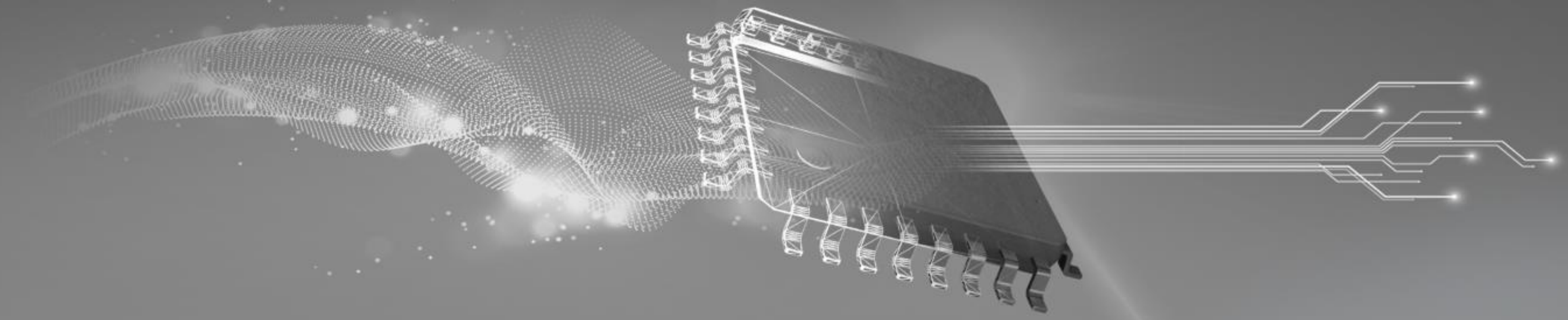
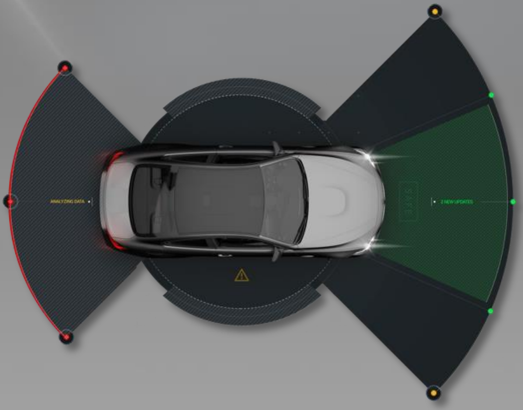
TI TECH DAYS



Time of Flight & LiDAR:
Optical Analog Front End Design



Anthony Vaughan

High Speed Amplifiers

TEXAS INSTRUMENTS

Agenda

- Introduction to LiDAR
- Common LiDAR Architectures
- LiDAR Optical Front End Design
- TI LiDAR reference designs & products
- Key discussion points / Q&A

Agenda

- Introduction to LiDAR
- Common LiDAR Architectures
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- TI LiDAR reference designs & products
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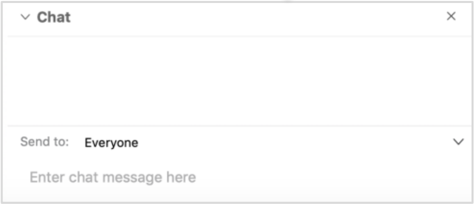
Use the Webex Chat



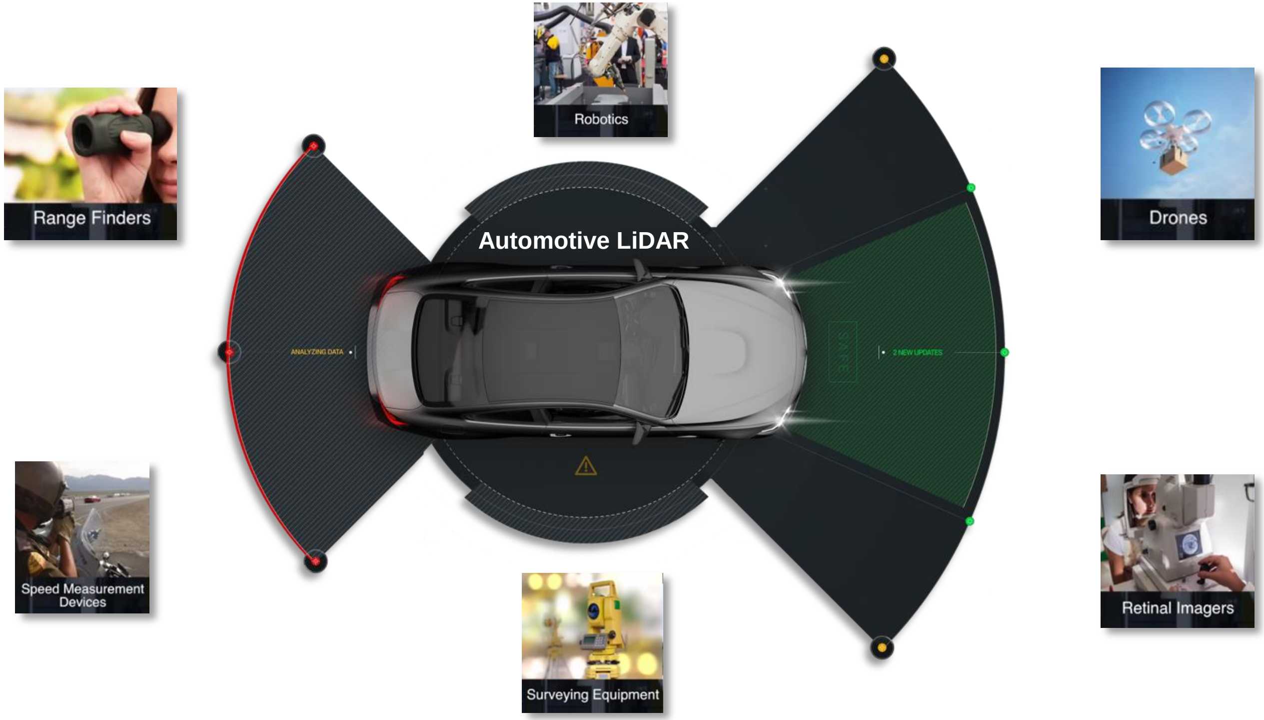
About Me

Anthony Vaughan

- High Speed Amplifier Marketing (Tucson, AZ)
- Joined TI in 2002
  - Product/Test Engineering (DSP – Dallas, TX)
  - Applications Engineering (MCU - Stafford, TX)
  - Marketing (MCU - Stafford, TX)
  - Marketing (Precision ADC – Tucson, AZ)
  - Marketing (High Speed Amps – Tucson, AZ)
- TI liaison for University of Arizona Autonomous Vehicle Club
- Sponsored several senior design projects at UArizona *(LiDAR RC Car)*

Introduction to LiDAR

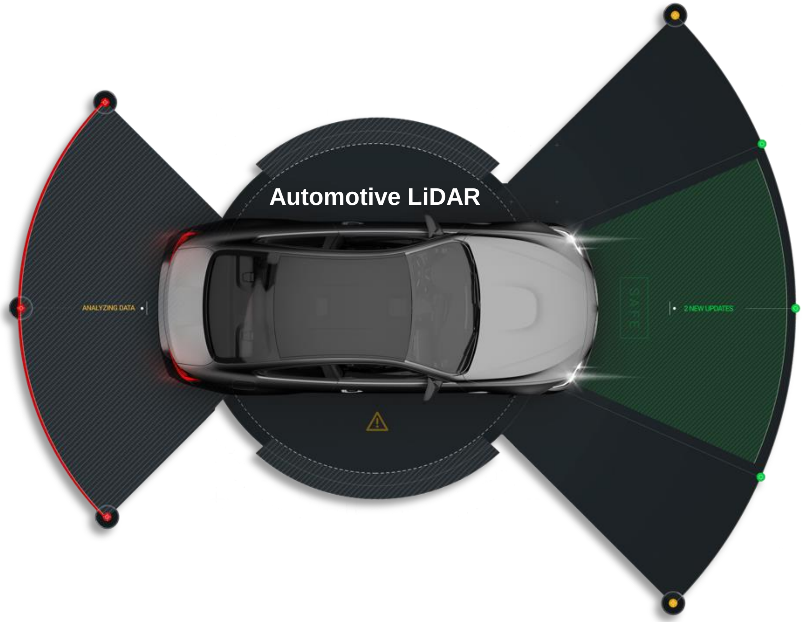
LiDAR: Light Detection and Ranging



TEXAS INSTRUMENTS

Introduction to LiDAR

LiDAR: Light Detection and Ranging



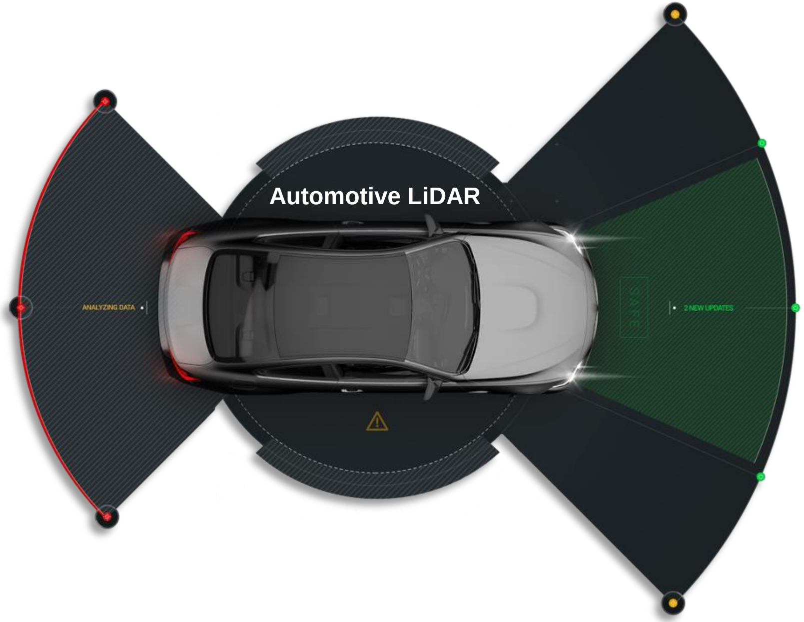
Question: True or False: Cars equipped with LiDAR based ADAS (Advanced Driver Assistance Systems) are available to purchase today.

A. True
B. False

Use the Webex polling feature to answer

Introduction to LiDAR

LiDAR: Light Detection and Ranging



Question: True or False: Cars equipped with LiDAR based ADAS (Advanced Driver Assistance Systems) are available to purchase today.

A. True ✓

~~B. False~~

The Audi A8 is available with an optional LiDAR system manufactured by Valeo (Scala® Gen 1).

Launched 2017

Image: Audi

Introduction to LiDAR

LiDAR: Light Detection and Ranging

Image: Waymo

Question: How many LiDAR modules does Waymo's Pacifica based autonomous robo-taxi use?

A. 1
B. 2
C. 3
D. 4
E. 5

Introduction to LiDAR

LiDAR: Light Detection and Ranging

Image: Waymo

Question: How many LiDAR modules does Waymo's Pacifica based autonomous robo-taxi use?

- ~~A. 1~~
- ~~B. 2~~
- ~~C. 3~~
- ~~D. 4~~
- E. 5 ✓

There are 4 short range LiDAR and 1 medium range LiDAR modules.

Introduction to LiDAR

LiDAR: Light Detection and Ranging

Image: Tesla

Question: True or False: Tesla's Autopilot 2 system uses the world's highest resolution LiDAR sensor.

A. True
B. False

Introduction to LiDAR

LiDAR: Light Detection and Ranging


Image: Tesla

Question: True or False: Tesla's Autopilot 2 system uses the world's highest resolution LiDAR sensor.

~~A. True~~
B. False ✓

The Tesla Autopilot system does not use LiDAR.

Introduction to LiDAR

LiDAR: Light Detection and Ranging

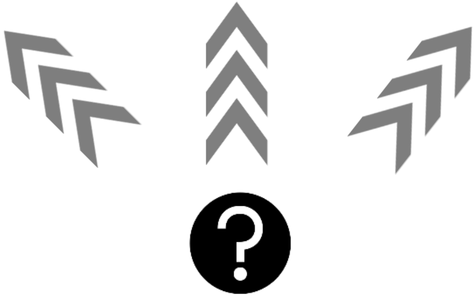
Lidar vs LiDAR vs LIDAR

Which one is correct

Introduction to LiDAR

LiDAR: Light Detection and Ranging

Lidar vs LiDAR vs LIDAR



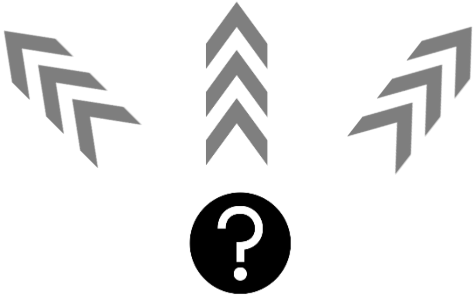
Which one is correct

Evolution from acronym to word

Introduction to LiDAR

LiDAR: Light Detection and Ranging

Lidar vs LiDAR vs LIDAR



Which one is correct

Evolution from acronym to word

This has happened before:

RADAR: RAdio **D**etection **A**nd **R**anging

Introduction to LiDAR

LiDAR: Light Detection and Ranging

Lidar vs LiDAR vs LIDAR

Which one is correct

What about LADAR

LADAR: Laser Detection and Ranging

Introduction to LiDAR

LiDAR: Light Detection and Ranging

Lidar vs LiDAR vs LIDAR

Which one is correct

What about LADAR

LADAR: Laser Detection and Ranging

light amplification by stimulated emission of radiation

Why do we need LiDAR?

Myth: Sonar, Radar & Cameras are adequate

Sonar

Advantages
- Inexpensive
- Works in all lighting conditions

Disadvantages
- Low resolution
- Limited range
- Slow response

Radar

Advantages
- Long range
- Works in most lighting & weather conditions

Disadvantages
- Medium resolution
- Medium response

Camera

Advantages
- High Resolution
- Can determine colors
- Inexpensive imagers

Disadvantages
- Poor distance measurement
- Poor low light performance
- Can be blinded with bright ambient light or bad weather

Why do we need LiDAR?

LiDAR Advantages

- Fast response time
- High resolution
- Can perform extremely accurate distance measurements
- Some systems can measure distance & velocity simultaneously
- Can quickly create a 3D image (point cloud)
- Works in most lighting conditions
- Does not require external illumination

Image: Valeo

Why do we need LiDAR?

LiDAR Disadvantages

- High cost (*prices are coming down quickly*)
- Limited distance (*ranges are increasing*)
- Poor performance in bad weather
- Some systems can have poor performance in bright sun light

Image: Valeo

Why do we need LiDAR?

LiDAR Disadvantages

- High cost (*prices are coming down quickly*)
- Limited distance (*ranges are increasing*)
- Poor performance in bad weather
- Some systems can have poor performance in bright sun light

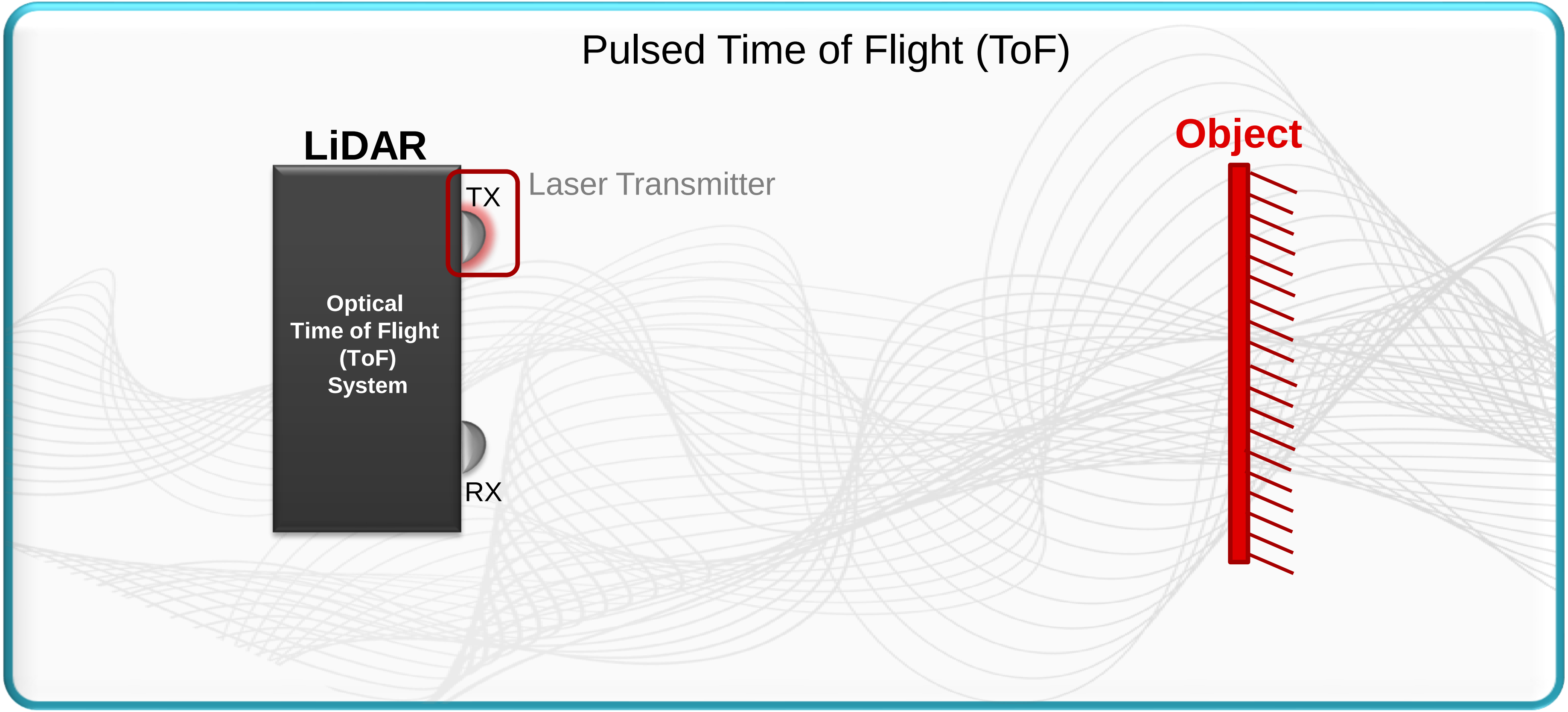
LiDAR will augment radar/camera/sonar in most automotive driver assistance systems.

Image: Valeo

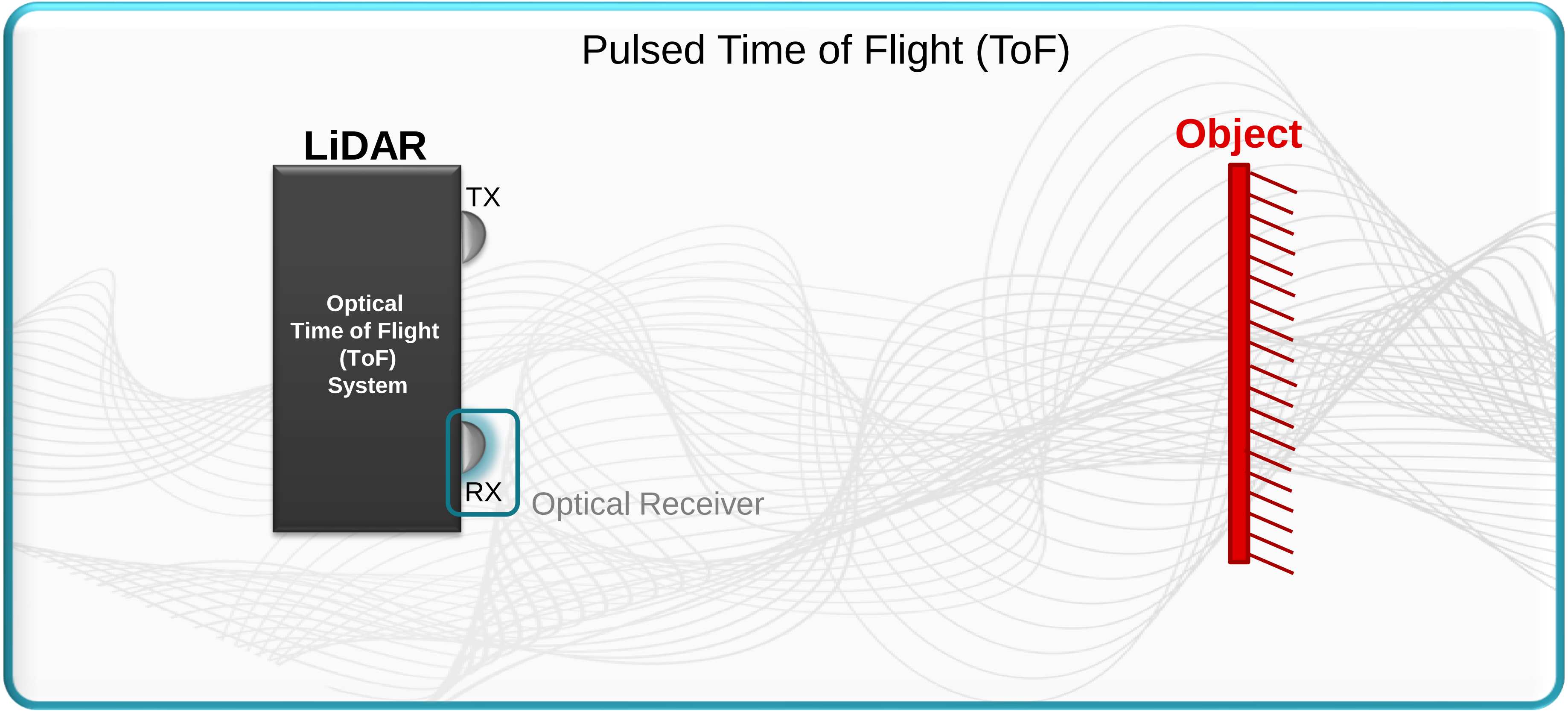
Basic LiDAR Principles

Pulsed Time of Flight (ToF)

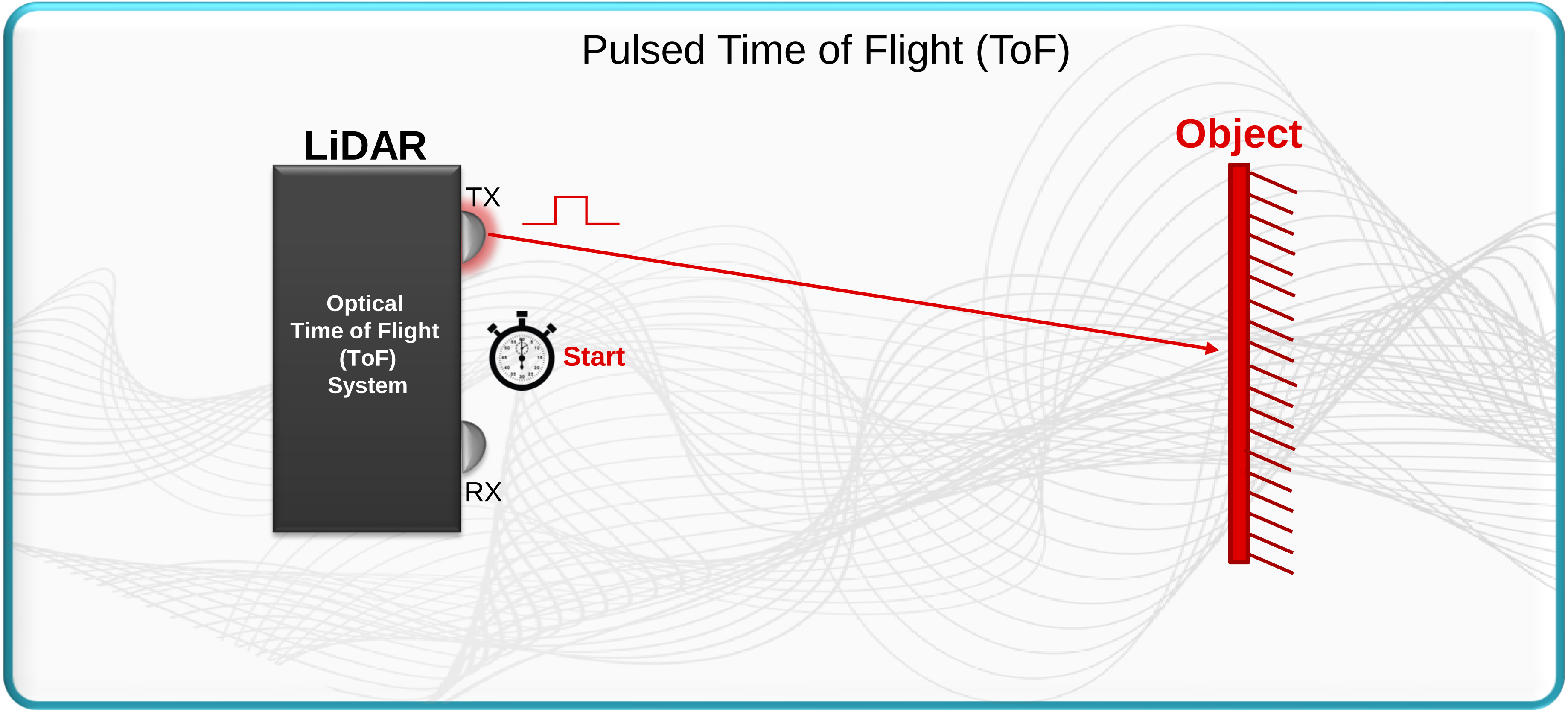
Basic LiDAR Principles



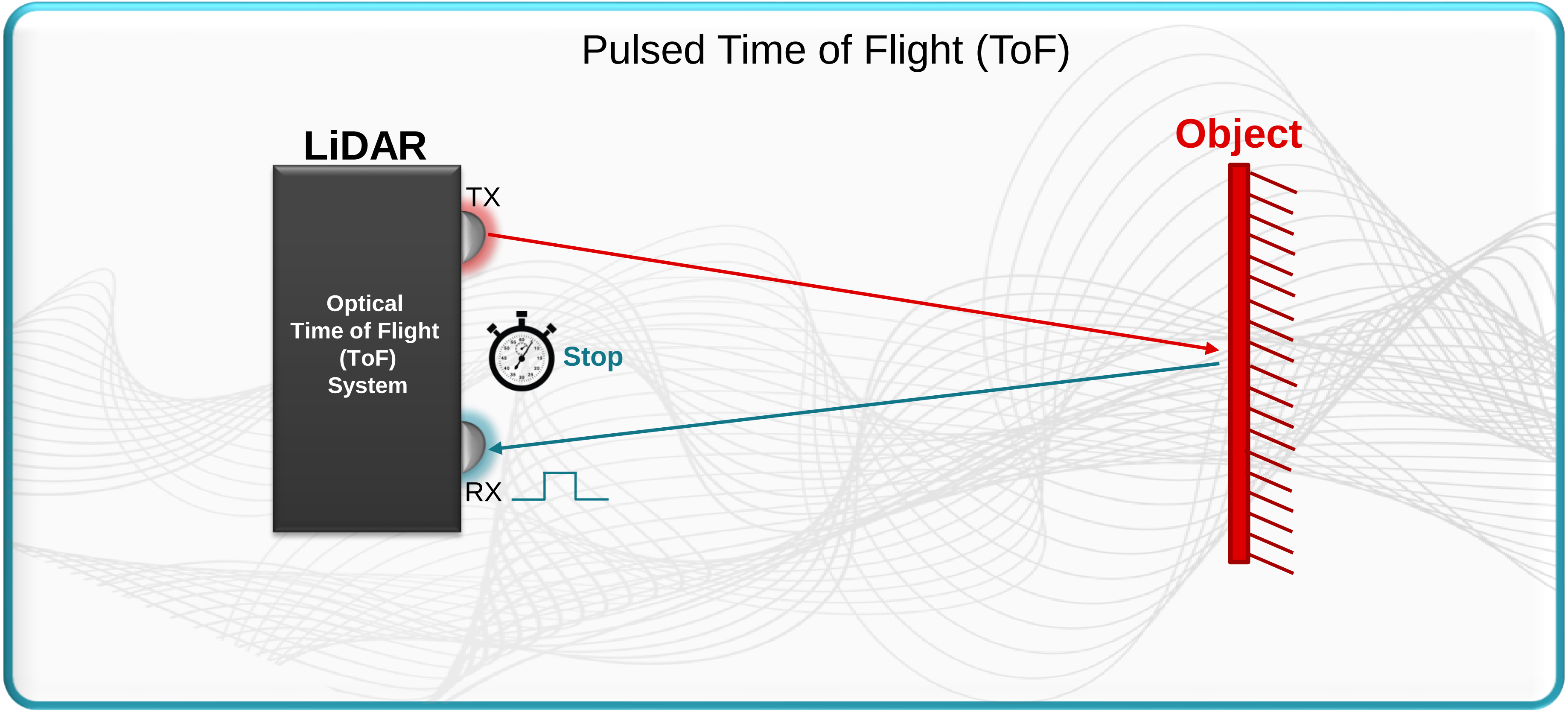
Basic LiDAR Principles



Basic LiDAR Principles

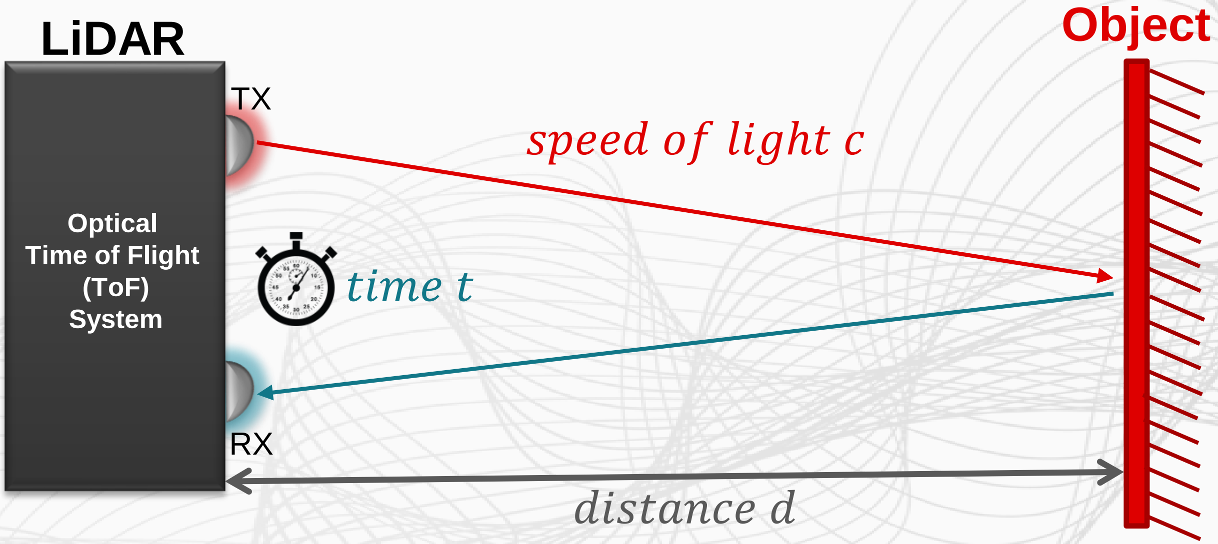


Basic LiDAR Principles



Basic LiDAR Principles

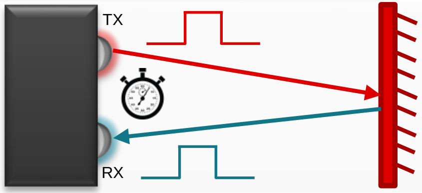
Pulsed Time of Flight (ToF)



$$d = \frac{c\,t}{2}$$

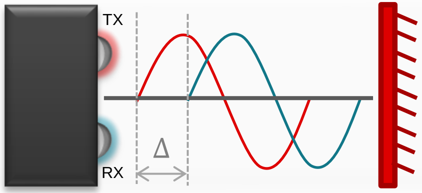
Common LiDAR Ranging Architectures

Pulsed Time of Flight



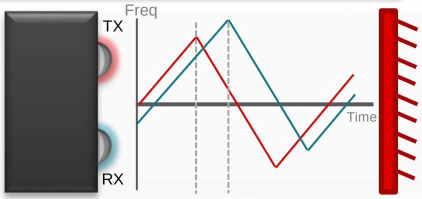
Pulsed Time of Flight takes a measurement of the time it takes a pulse of light to go from the transmitter to an object and back to the receiver.

Phase Shift



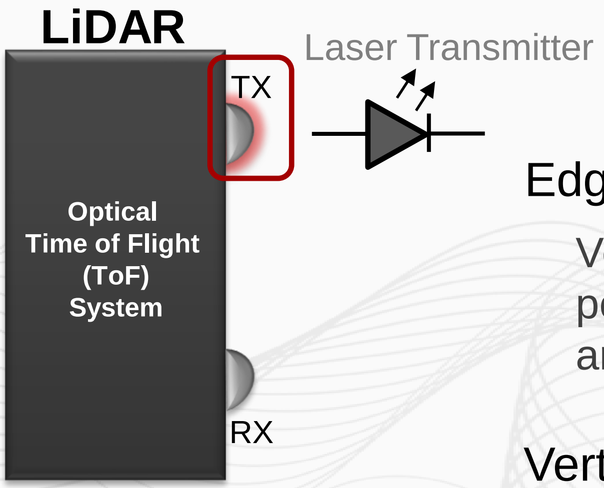
Phase Shift uses a continuous wave and measures the time of flight as a phase shift. The maximum distance is limited by phase wrapping.

Frequency Modulation



Frequency modulation (FMCW) uses a continuous wave with varying frequency and measures the time of flight as a frequency difference. Distance & velocity can be measured.

Laser Transmitter Types



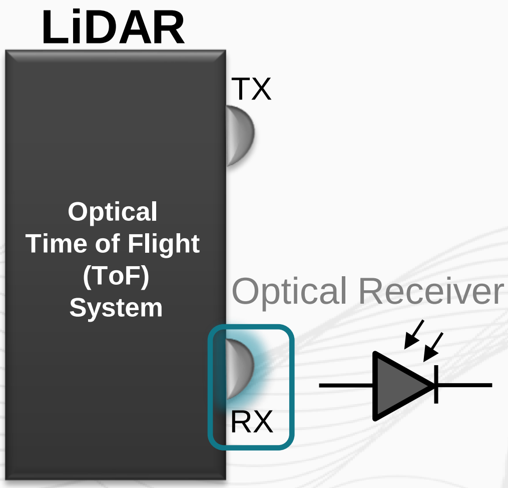
Edge Emitting Lasers (EEL):

Very mature technology that can provide very high power transmission. A wide variety of wavelengths are available. 830nm – 940nm & 1550nm

Vertical Cavity Surface Emitting Laser (VCSEL):

Newer technology that allow reduced cost manufacture of array transmitters. A wide variety of wavelengths are available. 830nm – 940nm & 1550nm

Laser Receiver Types



Pin Photo Diode:

Very mature technology that converts light in to an electrical current.

Avalanche Photo Diode (APD):

Newer photo diode technology that requires a high reverse bias for operation. APDs can provide very high gain due to the avalanche multiplication of the holes and electrons created by the photon/light.

Single Photon Avalanche Diode (SPAD):

Similar to APDs, but SPADs are designed to operate with a reverse bias voltage higher than the junction breakdown voltage providing even higher gain.

Silicon Photomultiplier (SiPM):

SiPMs provide very high sensitivity and dynamic range. They are made up of SPADs on a common silicon substrate

Scanning LiDAR

Scanning LiDAR is currently the most common LiDAR implementation

Scanning LiDAR

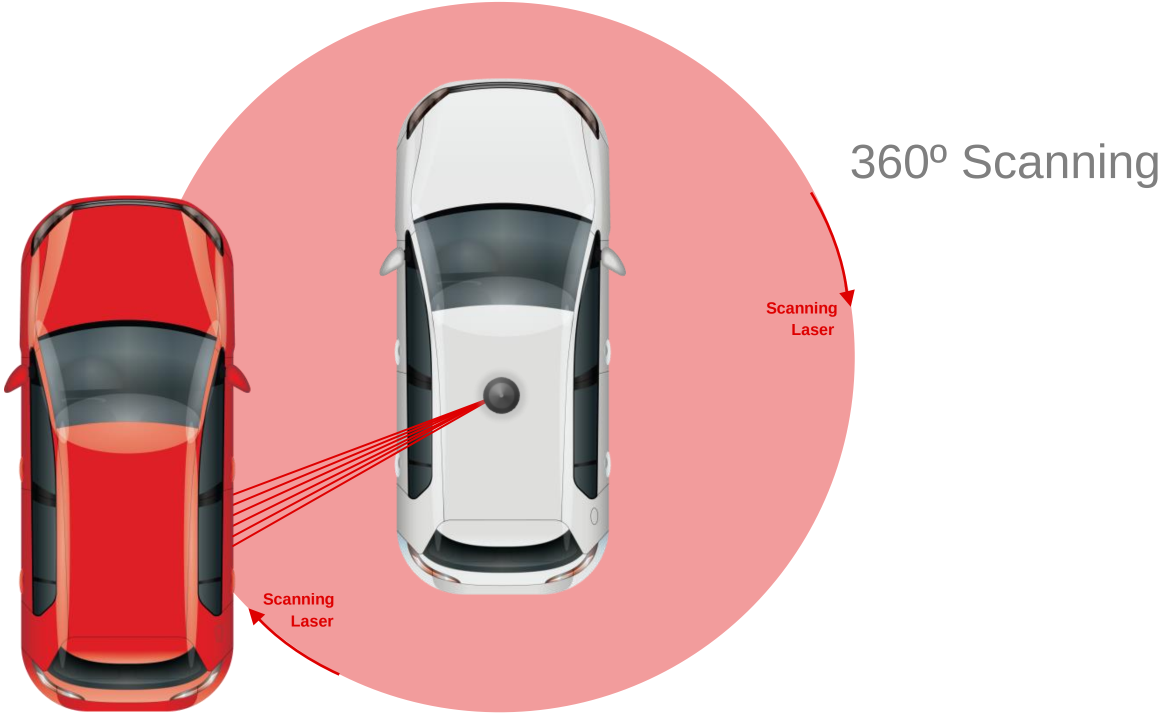
Most multi-channel scanning LiDAR systems need to scan either horizontally, vertically or both.

Horizonal Scanning

Vertical Scanning

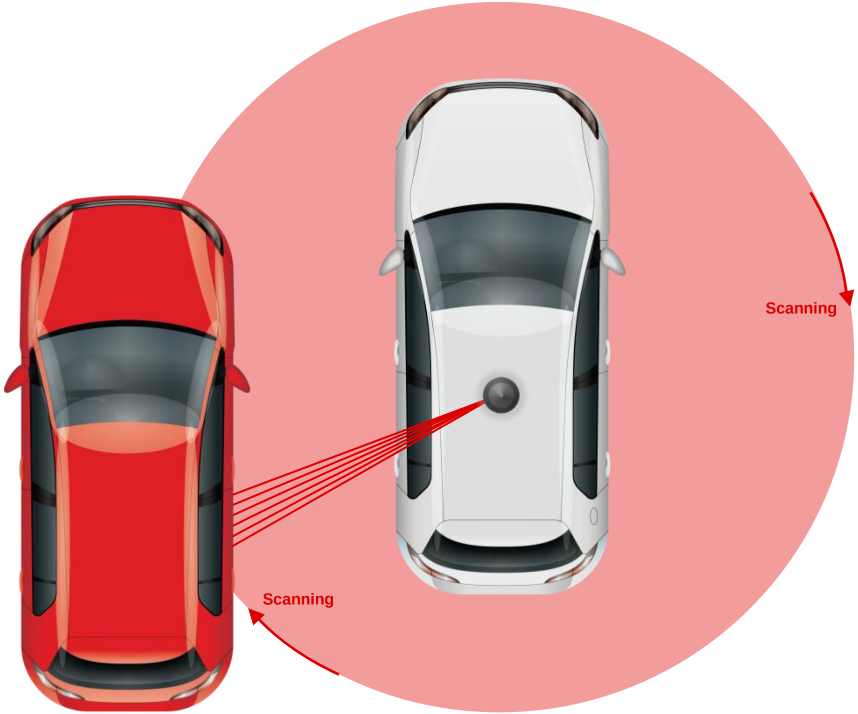
Scanning LiDAR

Some mechanically scanning LiDAR systems scan in a circle to provide a 360-degree view.



Scanning LiDAR

There are several different methods to implement scanning LiDAR.



Scanning LiDAR Methods:

Mechanical Scanning:

- Macro-mechanical
- Micro-motion
- Prisms

Solid State Scanning:

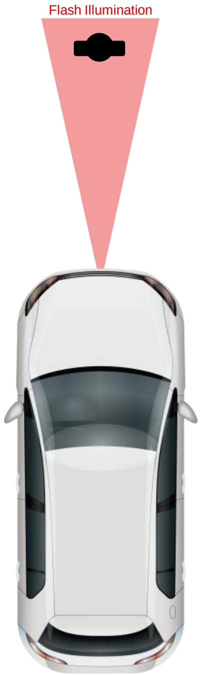
- MEMS
- Electro-optical
- Optical phased array

Flash LiDAR

Flash LiDAR is another implementation that does not require any moving parts.

Flash LiDAR

Flash LiDAR illuminates the entire scene and uses an array of photodetectors to form an image.



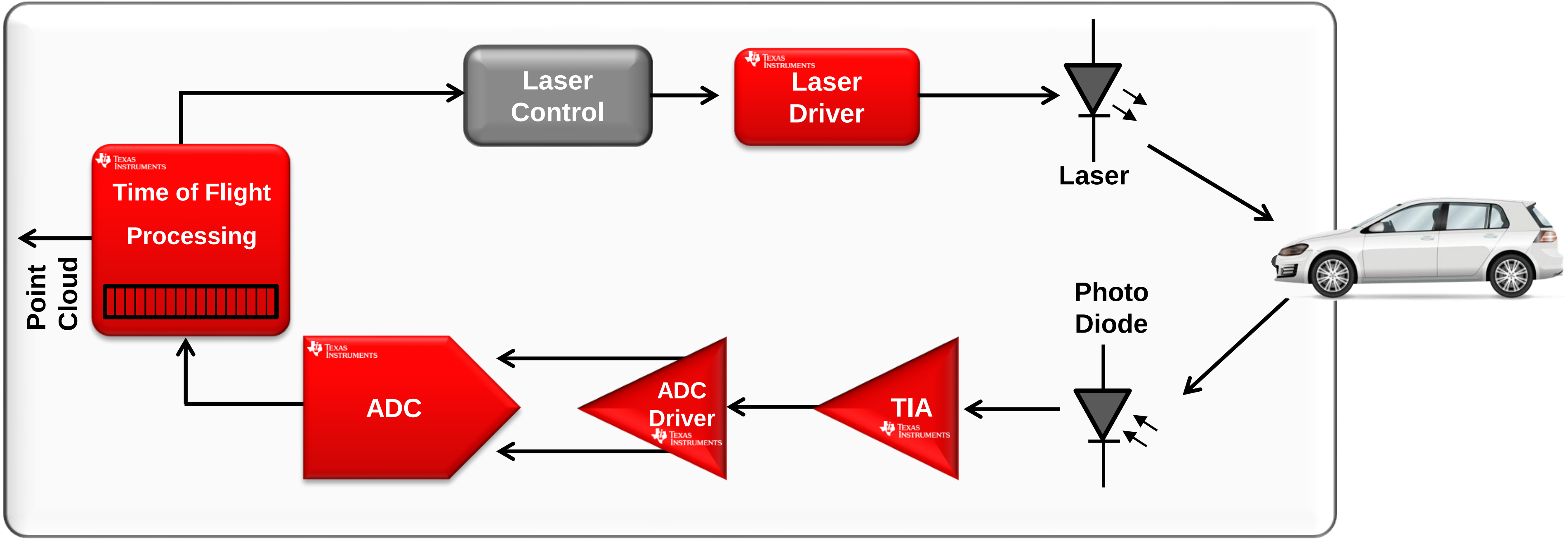
Flash LiDAR

Several types of photodetectors can be used in Flash LiDAR systems.

Flash LiDAR Photodetectors:

- Pin Diode Array
- Avalanche Photodiode Array
- SPAD Array
- Silicon Photomultiplier (SiPM)
- CCD Imager w/ ToF
- CMOS Imager w/ ToF

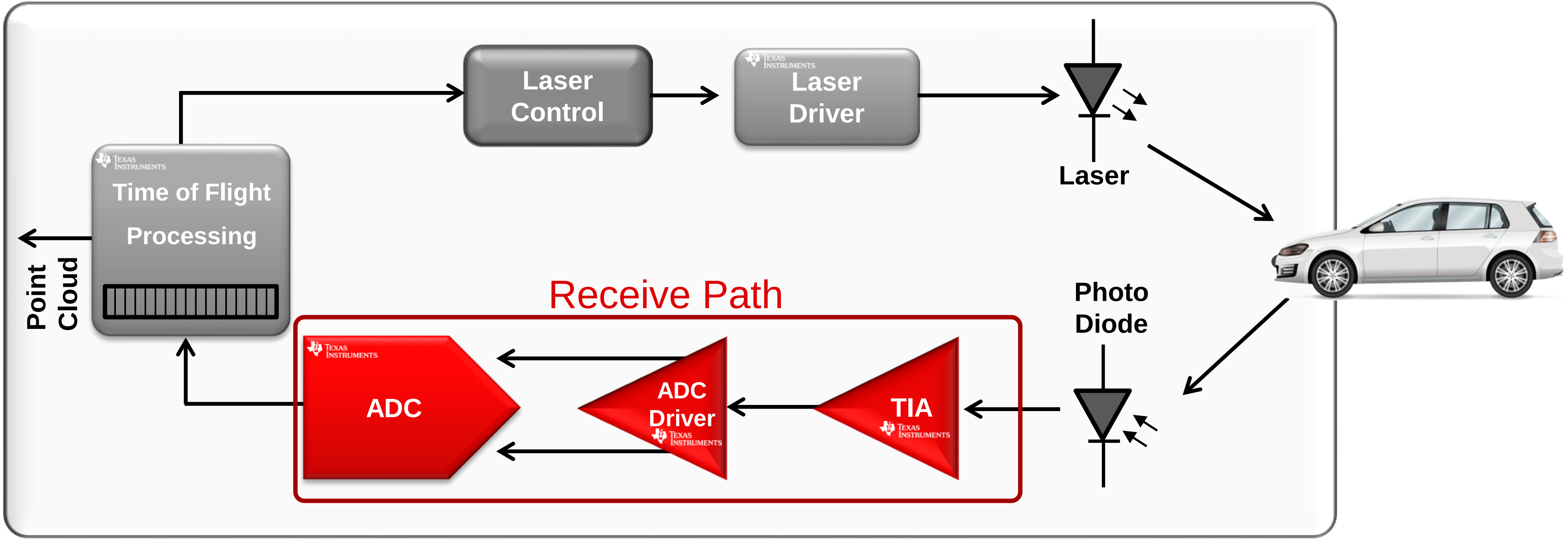
Automotive LiDAR System Block Diagram



Texas Instruments manufactures several products used in the LiDAR signal chain:

- **Receive Path:** Transimpedance amplifier, ADC Driver, ADC
- **Transmit Path:** Laser Driver
- **Processing:** Time of Flight Processing

Automotive LiDAR System Block Diagram



Texas Instruments manufactures several products used in the LiDAR signal chain:

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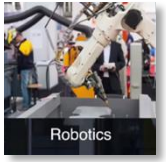
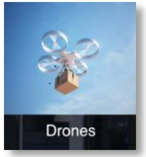
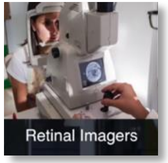
Texas Instruments LiDAR & Optical Time of Flight (ToF)

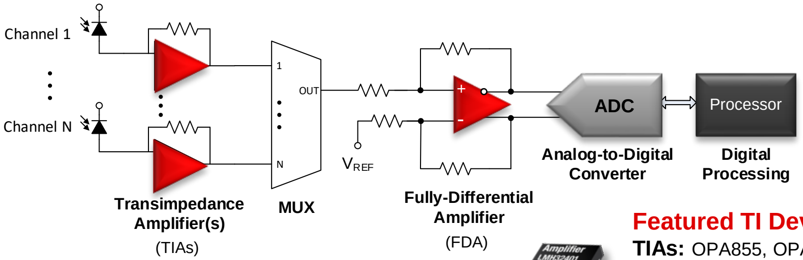


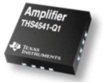




2 Optical ToF Receive Path Architectures:

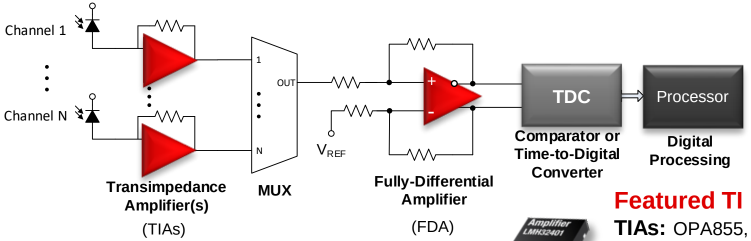
1 High-speed optical front end with Analog to Digital Converter (ADC)





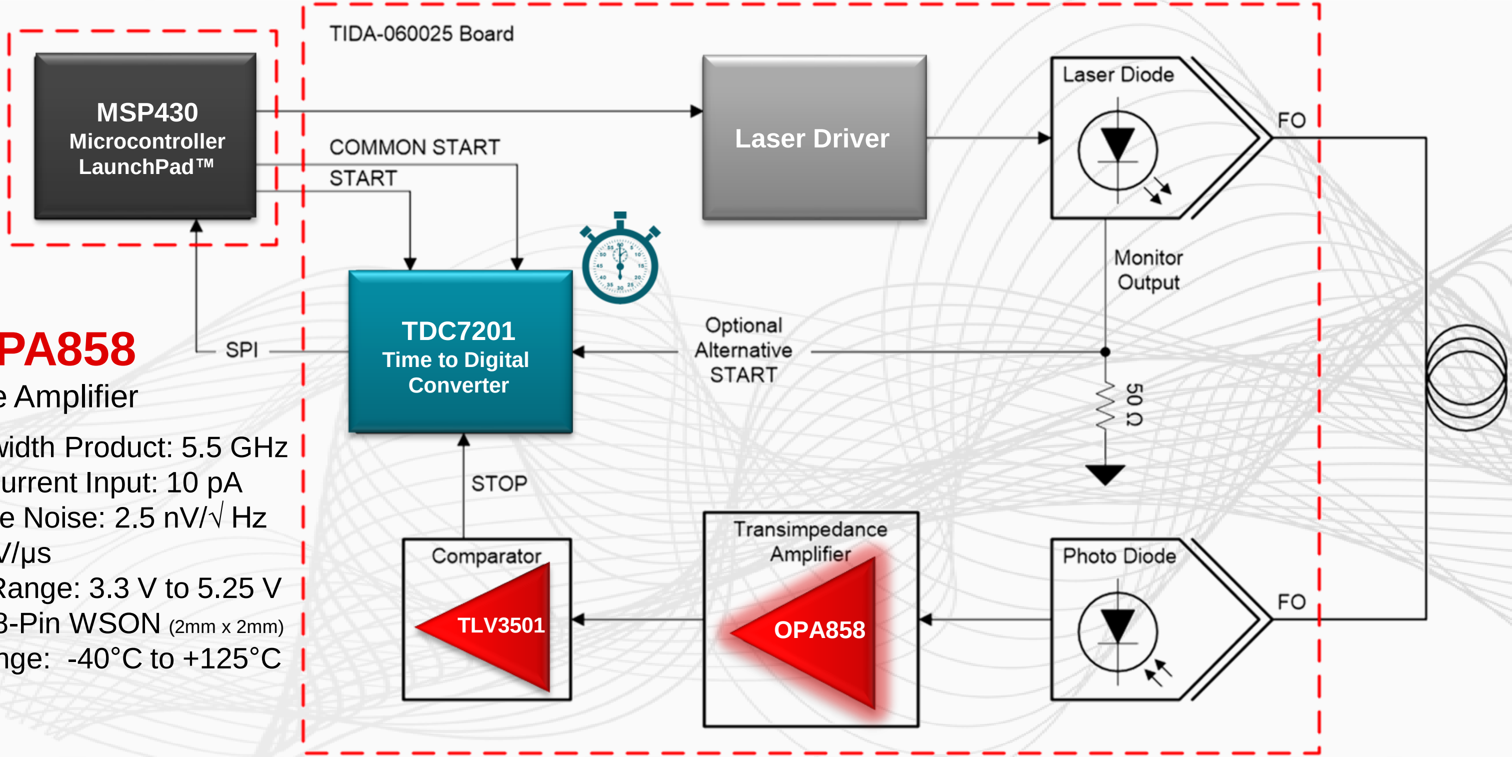
Featured TI Devices:
TIAs: OPA855, OPA857, OPA858
FDAs: THS4541
TIA + FDA: LMH32401
ADCs: ADC3244, ADC12QJ1600
Processors: TDA2, TDA3

2 High-speed optical front end with Time-to-Digital Converter (TDC)



Featured TI Devices:
TIAs: OPA855, OPA857, OPA858
FDAs: THS4541
TIA + FDA: LMH32401
TDC: TDC7201
Processors: MSP430, C2000

LiDAR Time of Flight System TDC Based Diagram



OPA858

Transimpedance Amplifier

- High Gain Bandwidth Product: 5.5 GHz
- Ultra-Low Bias Current Input: 10 pA
- Low Input Voltage Noise: 2.5 nV/√ Hz
- Slew rate: 2000 V/μs
- Supply Voltage Range: 3.3 V to 5.25 V
- Small Package: 8-Pin WSON (2mm x 2mm)
- Temperature Range: -40°C to +125°C

TIDA-060025 Maximizing Transimpedance Bandwidth for LIDAR and ToF

TIDesigns

Features

- Optical front-end design with demonstrated time-of-flight(ToF) measurement.
- High-speed amplifier signal path with bandwidth greater than 200 MHz at gain = 10 kΩ.
- Centimeter level measurement accuracy.
- High-speed transimpedance amplifier (TIA) for I-to-V conversion
- High-speed time-to-digital converter & low power MCU/processor

Benefits

- High speed transimpedance amplifier provides the closed loop bandwidth and gain sufficient for optical ToF applications.
- Low power/cost digital processing & control provides an efficient platform for highly accurate distance measurements.
- PC interface software provides quick and easy method to evaluate system performance and distance measurements.

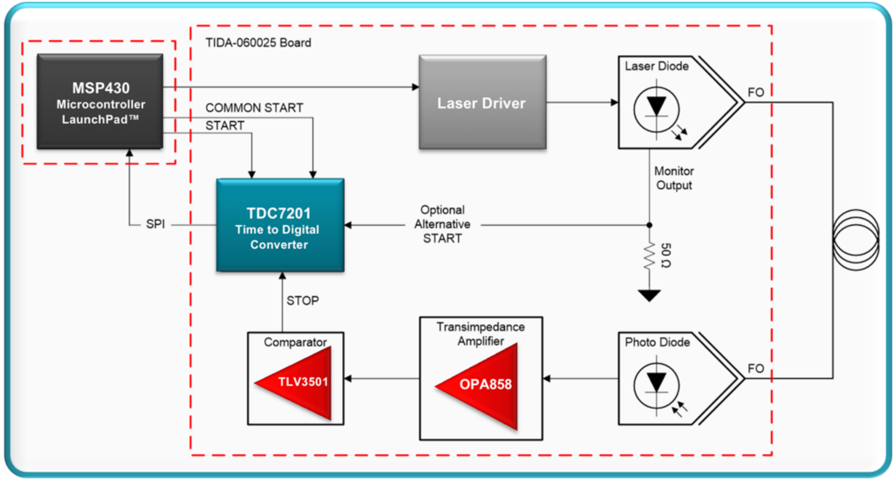
Applications

- Laser Distance Measurement
- LiDAR
- 3D Scanning
- EPOS
- Machine Vision
- Vacuum Robots
- Drone Vision
- OTDR

Tools & Resources

- **TIDA-060025 Web Site**
  - User Guide
- **Device Datasheets:**
  - OPA858
  - TDC7201
  - TLV3501
  - MSP430 MCU

TIDA-060025 System Block Diagram



Watch the Overview Video

Texas Instruments

LiDAR Time of Flight System ADC Based Diagram

Digital to Analog Converters:

DAC5682Z

- 1 GSPS
- 16-Bit Resolution

Analog to Digital Converters:

ADC3244

- 2 Channel, 125 MSPS
- 14-Bit Resolution

High Speed Amplifiers:

OPA695

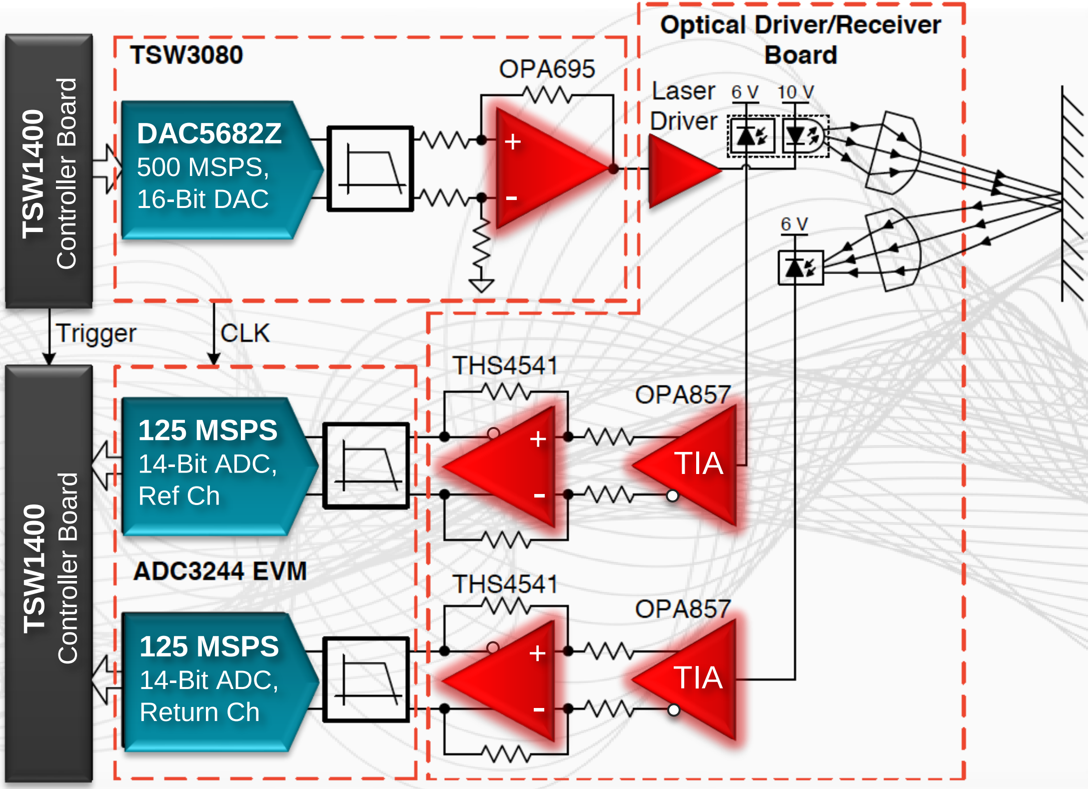
- 1.7 GHz, Current-Feedback Amplifier

OPA857

- Integrated Transimpedance Amplifier

THS4541

- 850 MHz, Fully Differential Amplifier



TIDA-01187 LIDAR-Pulsed Time-of-Flight Reference Design

TIDesigns

Features

- Measurement Range: 1.5 m to 9 m
- Range Measurement Mean Error of < ±6 mm and StdDev of < 3 cm
- 5.75W Pulsed 905 nm Laser Diode & Driver with < 1mW Average Power
- PIN Photodiode High Speed Transimpedance Amp Front End
- 125 MSPS 14-bit ADC and 500 MSPS 16-bit DAC Signal Chains
- Laser Collimation and Photoreceiver Focusing Optics
- Pulsed ToF Measurement Method with DFT based Range Estimation

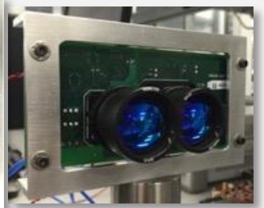
Benefits

- High resolution ADC simplifies front end circuitry
  - Eliminates variable gain amplifiers (VGA) and time discriminators
- ADC improves performance over comparator solutions while keeping power low
  - Improved Resolution
  - Elimination of Walk
  - Target Detection

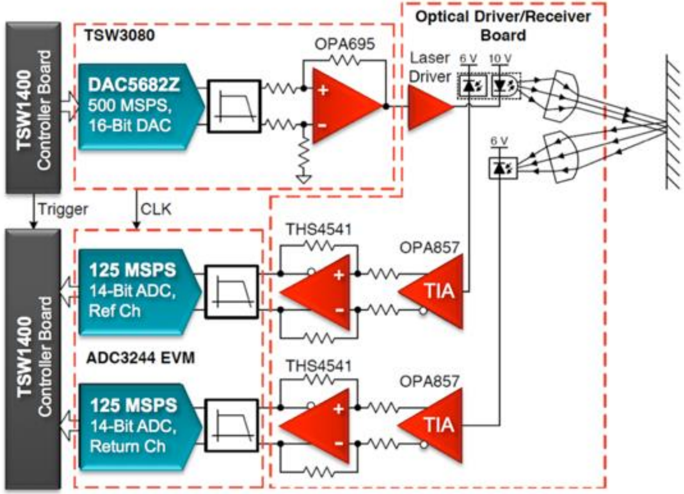
Applications

- Laser Safety Scanners and Range Finders (LiDAR)
- Architectural Surveying Equipment
- Automotive ADAS, Drones & Robotics
- Retinal Imaging

Tools & Resources



- **TIDA-01187 Web Site**
  - User Guide
- **Device Datasheets:**
  - ADC3244
  - DAC5682Z
  - OPA857
  - THS4541
  - OPA695



Watch the Overview Video

Texas Instruments

OPA85x Device Family Comparison

Name	Input Type	Gain BW	Stable Gain	Applications Benefit
Q100 OPA855	Bipolar	8.0 GHz	7 V/V	Best noise at lower gains Highest bandwidth possible **Production**
OPA856	Bipolar	1.2 GHz (BW)	Unity	Unity gain suitable for clamping Good noise performance for low gains **Coming Soon!**
OPA857	FET	130MHz closed loop @ 5kΩ 105MHz closed loop @ 20kΩ		Integrated gain settings for 5kΩ and 20kΩ transimpedance gains **Production**
Q100 OPA858	FET	5.5 GHz	7 V/V	Best noise performance at high gains High bandwidth and low input current **Production**
Q100 OPA859	FET	900 MHz (BW)	Unity	Maximum application flexibility Good high gain noise performance **Production**

AEC Q100 automotive devices in development

LMH32401

Low-Noise, High-Speed, Differential Output Transimpedance Amplifier

Features

- Closed-loop bandwidth: 500 MHz/275 MHz with C_{APD} = 1 pF
- Total Transimpedance Gain: 2 kΩ / 20 kΩ
- I_Q: 30 mA (typ.), Shutdown pin for low power mode
- Single supply: 3.3 V
- Integrated 100 mA clamp
- 1.5V_{PP} differential output swing
- Input referred noise: 10.5/3 pA/√Hz (C_{APD} = 1pF, Noise integrated to f_{-3dB} and input referred)
- Integrated ambient light cancellation
- Output Hi-Z in Disable eliminates the need for multiplexing

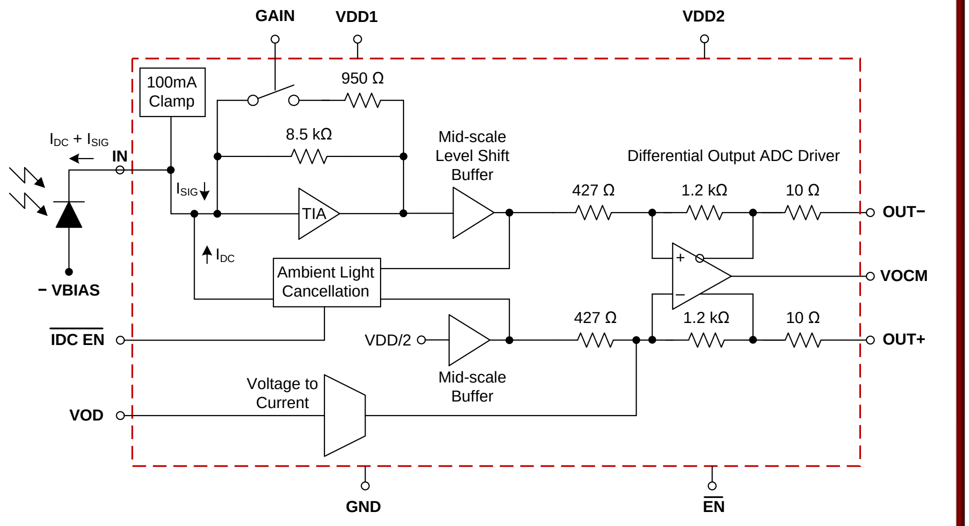
Package	Body Size
16-pin VQFN	3mm × 3mm

Applications

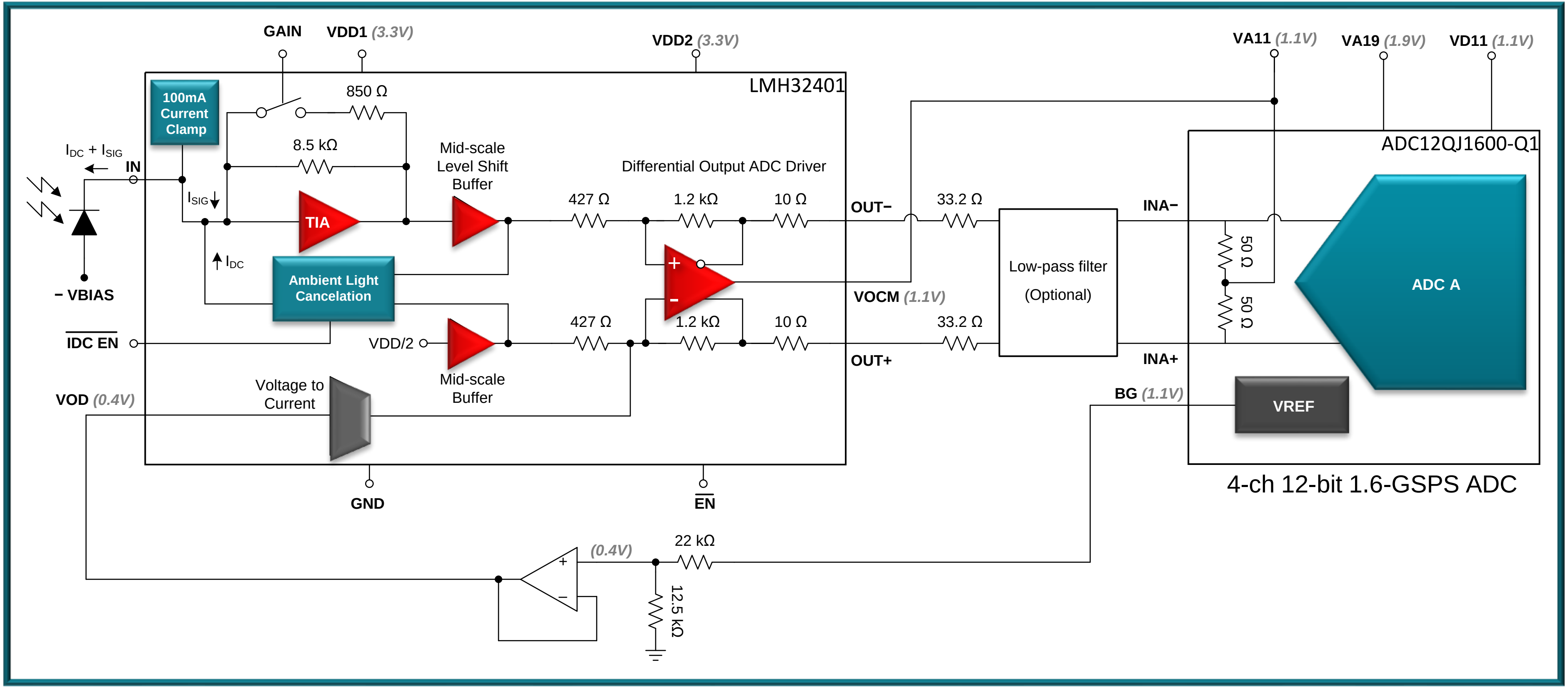
- Vacuum robots
- Topography scanner
- Safety Scanner
- Robotic and Auto. LiDAR
- Laser distance measurement
- Laser Gas Analysis

Benefits

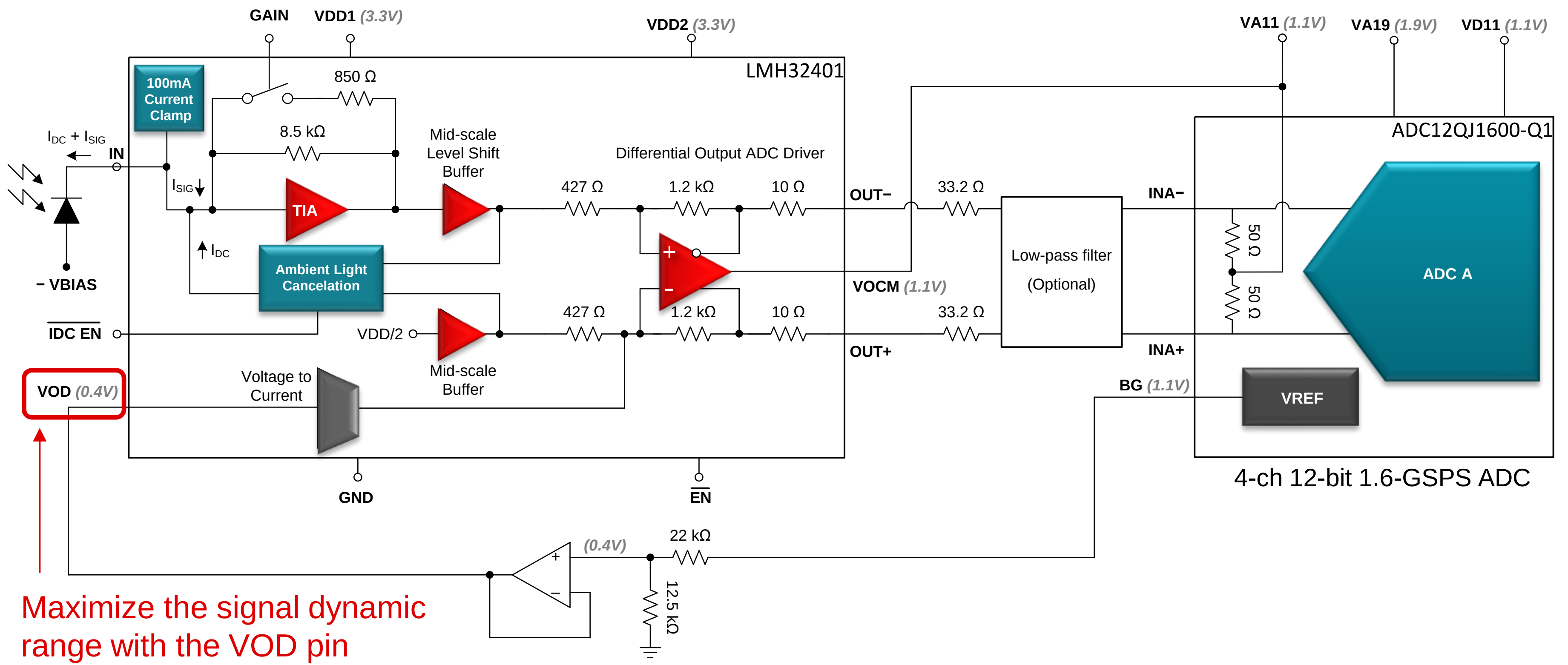
- High-speed TIA for fast-settling applications.
- Integrated clamping optimized for common-anode bias.
- Integrated ambient light cancellation saves PCB space and BOM cost.



LMH32401 & ADC12QJ1600 Receive Path Solution



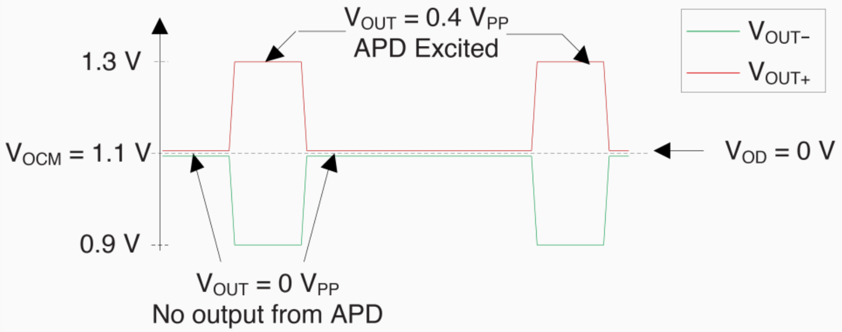
LMH32401 & ADC12QJ1600 Receive Path Solution



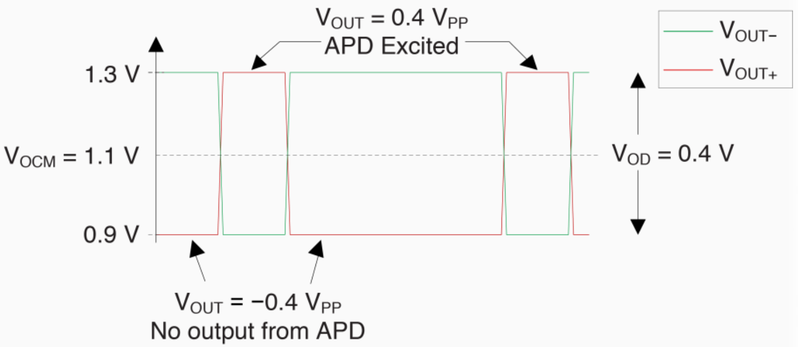
Maximize the signal dynamic range with the VOD pin

LMH32401 VOD Input to Maximize Dynamic Range

VOD = 0V



VOD = 0.4V



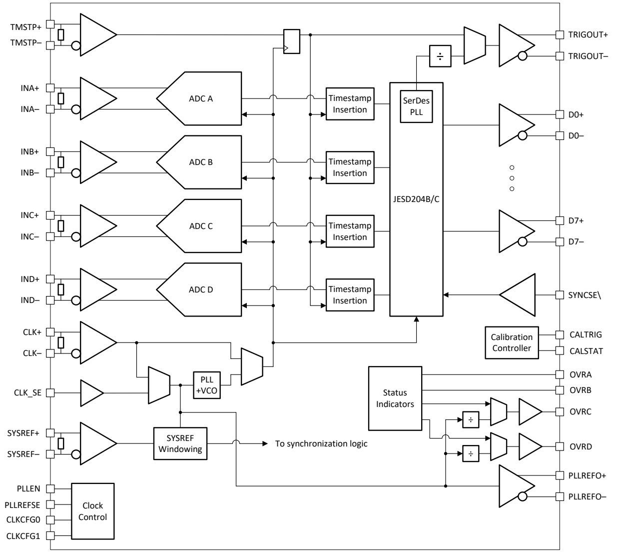
ADC12QJ1600/800-Q1

12-Bit, Quad Channel, 1.6 Gsps ADC

Features

- **ADC Core:** Quad 12-bit 1.6 Gsps
- **Non-Interleaved ADC core:** No interleaving spurs
- **Internal Dither:** Improved high-order spurs, backoff performance
- **Power Consumption:** 1.9 W total (1 Gsps, PLL disabled)
- **Integrated PLL and VCO:** Simplified system clocking architecture
- **Buffered Inputs:** 6-GHz Input Bandwidth (-3 dB)
- **Input Full-Scale Voltage:** 0.8 Vpp (Adjustable, 0.5 Vpp to 1.0 Vpp)
- **SNR @ 100 MHz:** 56.8 dBFS (800 mVpp)
- **ENOB @ 100 MHz:** 9.1-bit
- **Code-Error Rate:** 10^{-18}
- **Digital Interface:** JESD204B/C with subclass 1 support
- **Serdes Lanes and Speeds:** Up to 8 lanes @ up to 17.16 Gbps
- **Reduced Resolution Options:** 10-bit and 8-bit options available to reduce interface speed or number of lanes
- **Timestamp and Trigger Output:** Reduce system complexity and retime trigger signals to internal sampling clock
- **Power supplies:** 1.1V, 1.9V
- **Package:** BGA (10x10mm, 0.8mm pitch)
- **Automotive Qualification:** AEC-Q100 Grade 1 (-40 to 150°C)

Input Frequency (@ 1.6 Gsps, -1 dBFS)	100 MHz	1 GHz
SNR (dBFS, typ)	56.8	55.7
NSD (dBFS/Hz, typ)	-145.8	-144.7
SFDR (dBc, typ)	72	65
Non HD2,3 (dBc, typ)	75	70



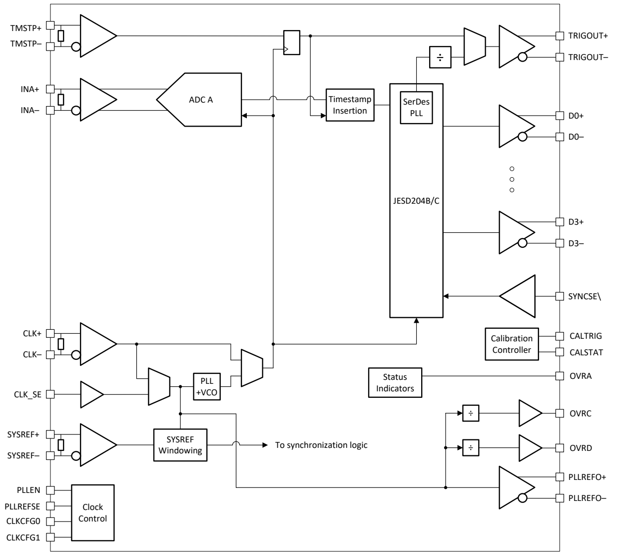
ADC12SJ1600/800-Q1

12-Bit, Single Channel, 1.6 Gsps ADC

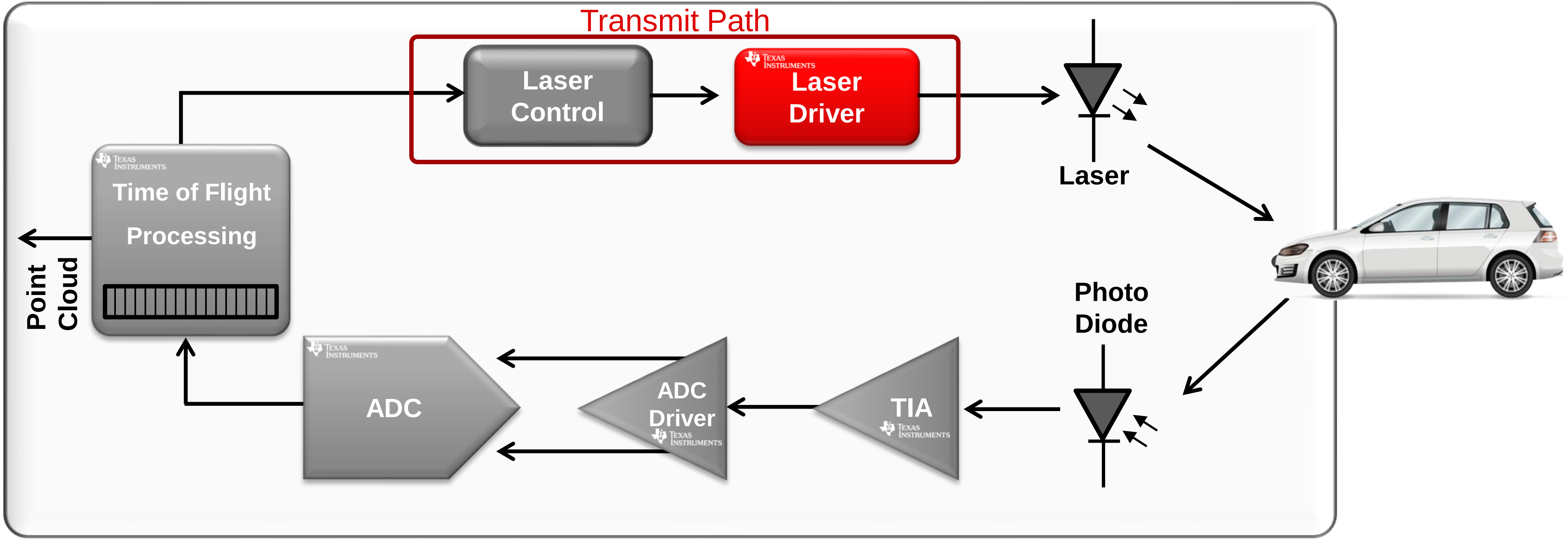
Features

- **ADC Core:** Single 12-bit 1.6 Gsps
- **Non-Interleaved ADC core:** No interleaving spurs
- **Internal Dither:** Improved high-order spurs, backoff performance
- **Power Consumption:** 900 mW total (1 Gsps, PLL disabled)
- **Integrated PLL and VCO:** Simplified system clocking architecture
- **Buffered Inputs:** 6-GHz Input Bandwidth (-3 dB)
- **Input Full-Scale Voltage:** 0.8 Vpp (Adjustable, 0.5 Vpp to 1.0 Vpp)
- **SNR @ 100 MHz:** 56.8 dBFS (800 mVpp)
- **ENOB @ 100 MHz:** 9.1-bit
- **Code-Error Rate:** 10^{-18}
- **Digital Interface:** JESD204B/C with subclass 1 support
- **Serdes Lanes and Speeds:** Up to 4 lanes @ up to 17.16 Gbps
- **Reduced Resolution Options:** 10-bit and 8-bit options available to reduce interface speed or number of lanes
- **Timestamp and Trigger Output:** Reduce system complexity and retime trigger signals to internal sampling clock
- **Power supplies:** 1.1V, 1.9V
- **Package:** BGA (10x10mm, 0.8mm pitch)
- **Automotive Qualification:** AEC-Q100 Grade 1 (-40 to 150°C)

Input Frequency (@ 1.6 Gsps, -1 dBFS)	100 MHz	1 GHz
SNR (dBFS, typ)	56.8	55.7
NSD (dBFS/Hz, typ)	-145.8	-144.7
SFDR (dBc, typ)	72	65
Non HD2,3 (dBc, typ)	75	70



Automotive LiDAR System Block Diagram



Texas Instruments manufactures several products used in the LiDAR signal chain:

- **Receive Path:** Transimpedance amplifier, ADC Driver, ADC
- **Transmit Path:** Laser Driver - LMG1025-Q1
- **Processing:** Time of Flight Processing

LMG1025-Q1: Automotive Low Side Driver For High Frequency, Narrow Pulse Applications

Features

- AEC-Q100 Grade 1 Qualification
- Capable of operating at very high switching frequency
- Independent pull-up (7A) and pull-down (5A) outputs
- Typical rise time of 650ps, fall time of 850ps
- Typical minimum input pulse width of 1.25 ns
- Typical propagation delay of 2.9ns
- Single 5V supply & under-voltage protection (UVLO)
- Inverting and non-inverting inputs

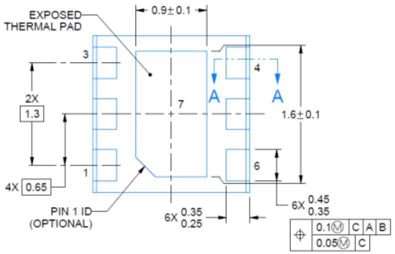
Benefits

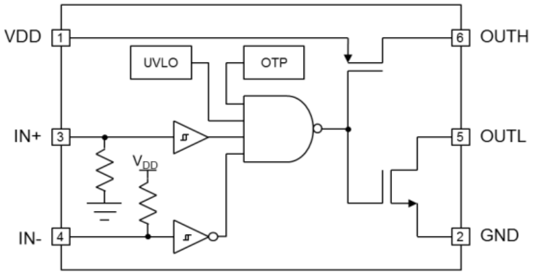
- Narrow pulse width allows increase in power/current level while still maintaining eye safety
- Switches at Frequencies needed for LED Drive in LiDAR
- Independent outputs allow for setting up different rise and fall time as required by the application
- Small distortion enables precise image mapping
- Small, leadless package enables layout optimization

Applications

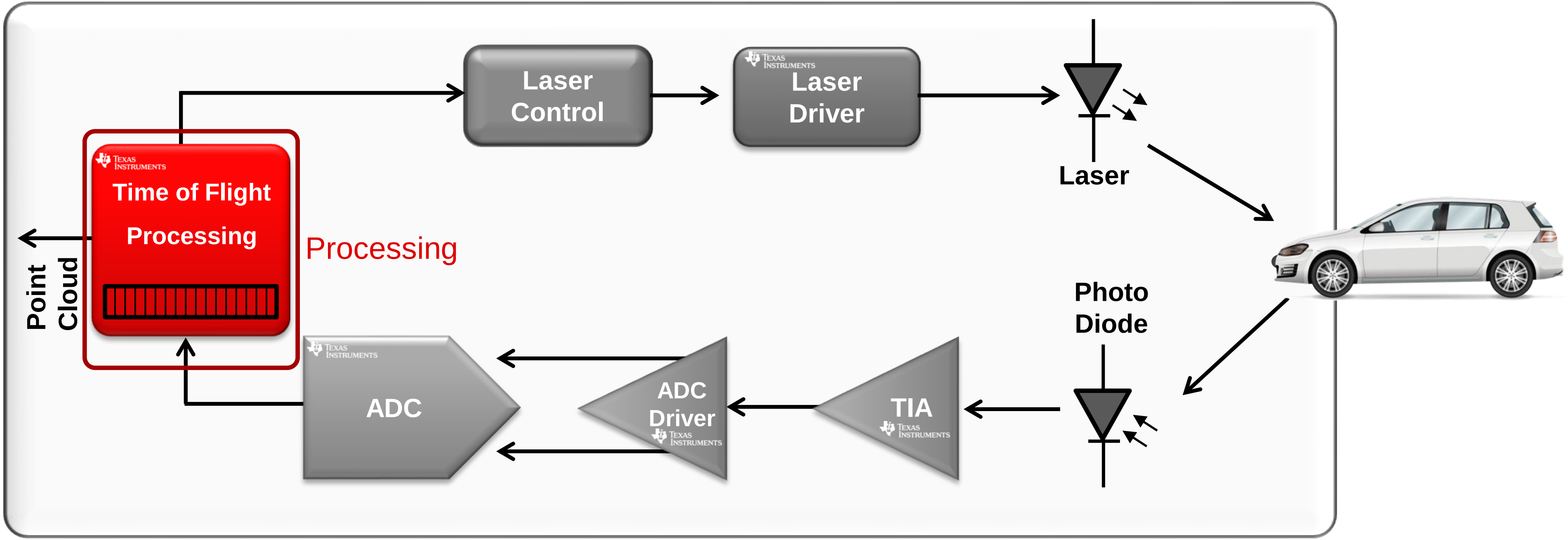
- LiDAR
- 3D ToF Laser Drivers
- Occupant Monitoring

Application Diagram & Package Options



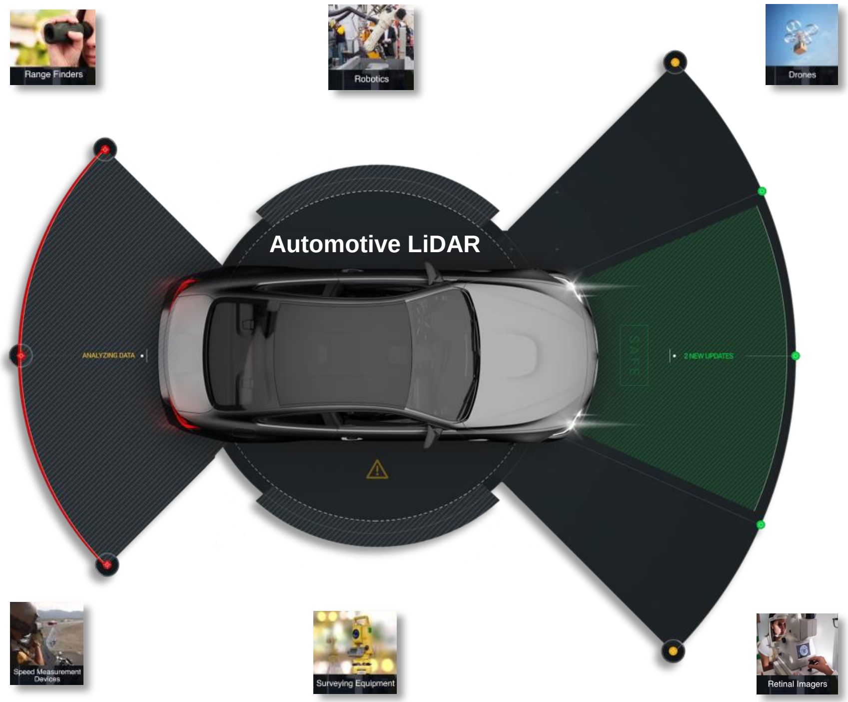


Automotive LiDAR System Block Diagram



Texas Instruments manufactures several products used in the LiDAR signal chain:

- **Receive Path:** Transimpedance amplifier, ADC Driver, ADC
- **Transmit Path:** Laser Driver - LMG1025-Q1
- **Processing:** Time of Flight Processing: TDA2, TDA3



Time of Flight & LiDAR:
Optical Analog Front End Design

Questions & Answers

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