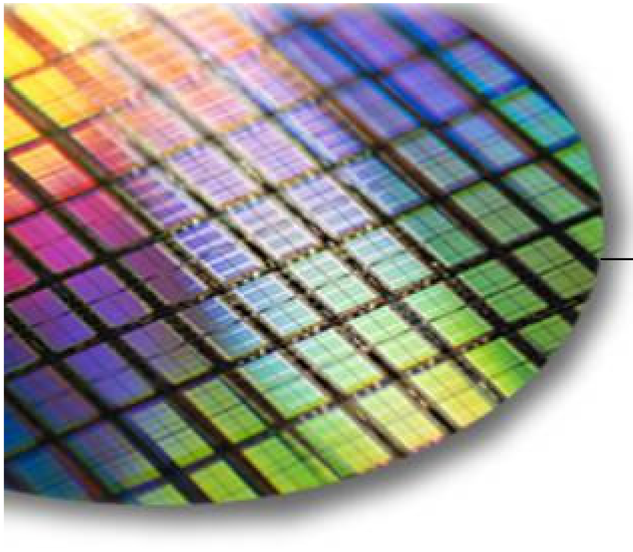


The World Leader in High Performance Signal Processing Solutions

Fractional-N PLL-Based Frequency Sweep Generator For FMCW Radar

Austin Harney, Analog Devices Inc.,

Rudolf Wihl, Analog Devices Inc.,

ANALOG DEVICES

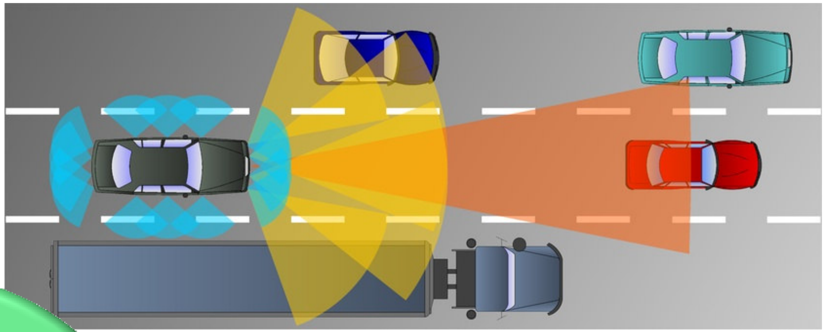
Analog Devices in ADAS

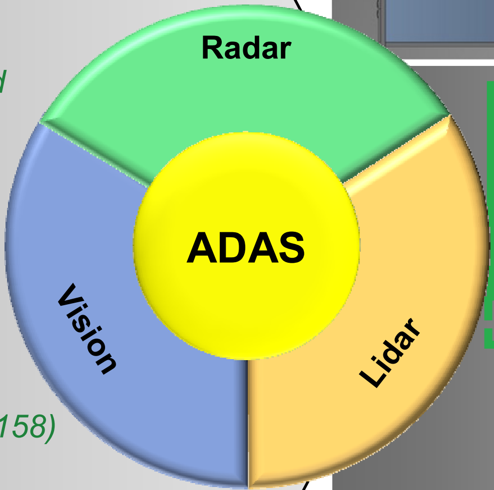
- *Analog Signal Processing*
  Leading Edge Performance, low cost , wide range of automotive qualified standard components ADC, DAC, MUX, Switches, LNA, VGA/PGA, PLL, Sensors, Video Encoder/Decoder

- *Digital Signal Processing*
  Blackfin and Sharc covering all ADAS application areas, automotive qualified and optimizes for performance/price/power-consumption

- *ASSP*
  Application Specific Standard Products, for further system integration and cost optimization.
  e.g. Integrated RADAR AFE (AD8283);
  e.g. Integrated Ramp/Chirp Timing (ADF4158)

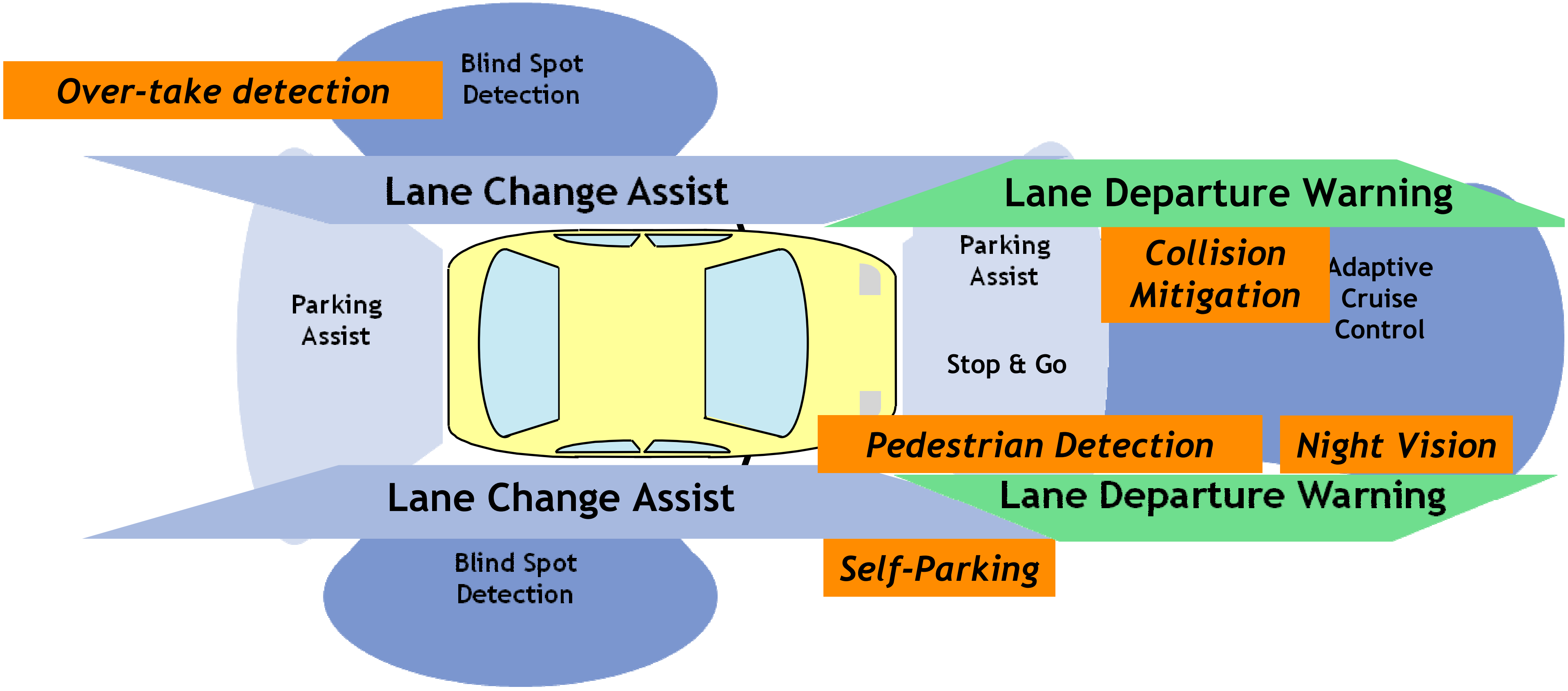
- *New System Architecture / IP*
  Enable unique ways to address and solve technical challenges or realize new applications concepts and areas. e.g. Lidar/Radar Baseband Modulation /Correlation Approach ;
  e.g. Optical Position Sensor





- *Adaptive Cruise Control*
- *Blind Spot Detection*
- *Lane Change Assist*
- *Pre-Crash Sensing*
- *Parking Assist*
- *Pedestrian Detection*
- *Lane Departure Warning*
- *Lane Keeping*
- *Birds-eye view*
- *Sensor Fusion*
- *NaVision*
- *NightVision*

ADAS – Multiple Systems / *Continued Evolution*



Automotive Lidar Status

- **Reasons Why Lidar Is In Decline**
  - Sensitive to environmental conditions (rain, spray, fog, snow, dirt)
  - Mounting position
  - Cost for Laser Diode and APD, especially for electronic scanning systems
- **Advantage of Lidar vs. Radar**
  - wide field of view, up to 360° for mechanical scanning system
  - excellent angular and distance resolution

When was RADAR invented?

Radar: A 105 year-old "Baby“
Patent-Paper from 1905

Eigentum des Kaiserlichen Patentamts. Eingefügt der Sammlung für Unterklasse ... Gruppe Nr. ...

KAISERLICHES PATENTAMT.

AUSGEGEBEN DEN 21. NOVEMBER 1905.

PATENTSCHRIFT

— № 165546 —

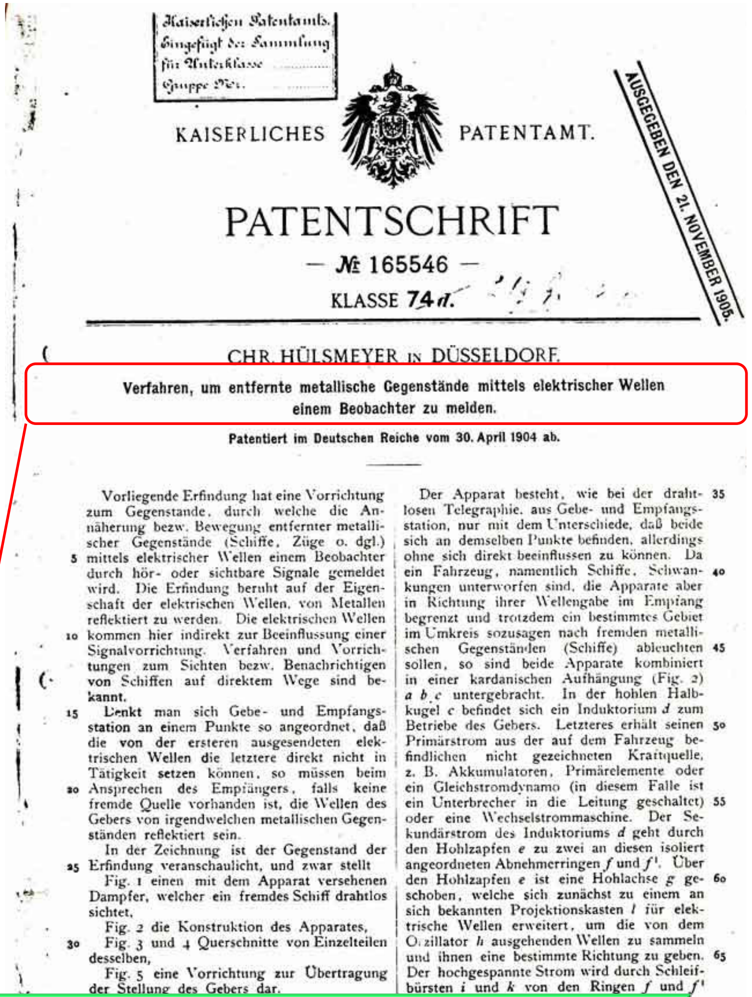
KLASSE 74a.

CHR. HÜLSMEYER IN DÜSSELDORF.

Verfahren, um entfernte metallische Gegenstände mittels elektrischer Wellen einem Beobachter zu melden.

Patentiert im Deutschen Reiche vom 30. April 1904 ab.

Fig. 1.



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Vorliegende Erfindung hat eine Vorrichtung zum Gegenstande, durch welche die Annäherung bezw. Bewegung entfernter metallischer Gegenstände (Schiffe, Züge o. dgl.) mittels elektrischer Wellen einem Beobachter durch hör- oder sichtbare Signale gemeldet wird. Die Erfindung beruht auf der Eigenschaft der elektrischen Wellen, von Metallen reflektiert zu werden. Die elektrischen Wellen kommen hier indirekt zur Beeinflussung einer Signalvorrichtung. Verfahren und Vorrichtungen zum Sichten bezw. Benachrichtigen von Schiffen auf direktem Wege sind bekannt.

Denkt man sich Gebe- und Empfangsstation an einem Punkte so angeordnet, daß die von der ersteren ausgesendeten elektrischen Wellen die letztere direkt nicht in Tätigkeit setzen können, so müssen beim Ansprechen des Empfängers, falls keine fremde Quelle vorhanden ist, die Wellen des Gebers von irgendwelchen metallischen Gegenständen reflektiert sein.

In der Zeichnung ist der Gegenstand der Erfindung veranschaulicht, und zwar stellt

Fig. 1 einen mit dem Apparat versehenen Dampfer, welcher ein fremdes Schiff drahtlos sichtet,

Fig. 2 die Konstruktion des Apparates,

Fig. 3 und 4 Querschnitte von Einzelteilen desselben,

Fig. 5 eine Vorrichtung zur Übertragung der Stellung des Gebers dar.

Der Apparat besteht, wie bei der drahtlosen Telegraphie, aus Gebe- und Empfangsstation, nur mit dem Unterschiede, daß beide sich an demselben Punkte befinden, allerdings ohne sich direkt beeinflussen zu können. Da ein Fahrzeug, namentlich Schiffe, Schwankungen unterworfen sind, die Apparate aber in Richtung ihrer Wellengabe im Empfang begrenzt und trotzdem ein bestimmtes Gebiet im Umkreis sozusagen nach fremden metallischen Gegenständen (Schiffe) ableuchten sollen, so sind beide Apparate kombiniert in einer kardanischen Aufhängung (Fig. 2) *a b c* untergebracht. In der hohlen Halbkugel *c* befindet sich ein Induktorium *d* zum Betriebe des Gebers. Letzteres erhält seinen Primärstrom aus der auf dem Fahrzeug befindlichen nicht gezeichneten Kraftquelle, z. B. Akkumulatoren, Primärelemente oder ein Gleichstromdynamo (in diesem Falle ist ein Unterbrecher in die Leitung geschaltet) oder eine Wechselstrommaschine. Der Sekundärstrom des Induktoriums *d* geht durch den Hohlzapfen *e* zu zwei an diesen isoliert angeordneten Abnehmerringen *f* und *f'*. Über den Hohlzapfen *e* ist eine Hohlachse *g* geschoben, welche sich zunächst zu einem an sich bekannten Projektionskasten *l* für elektrische Wellen erweitert, um die von dem Oszillator *h* ausgehenden Wellen zu sammeln und ihnen eine bestimmte Richtung zu geben. Der hochgespannte Strom wird durch Schleifbürsten *i* und *k* von den Ringen *f* und *f'*

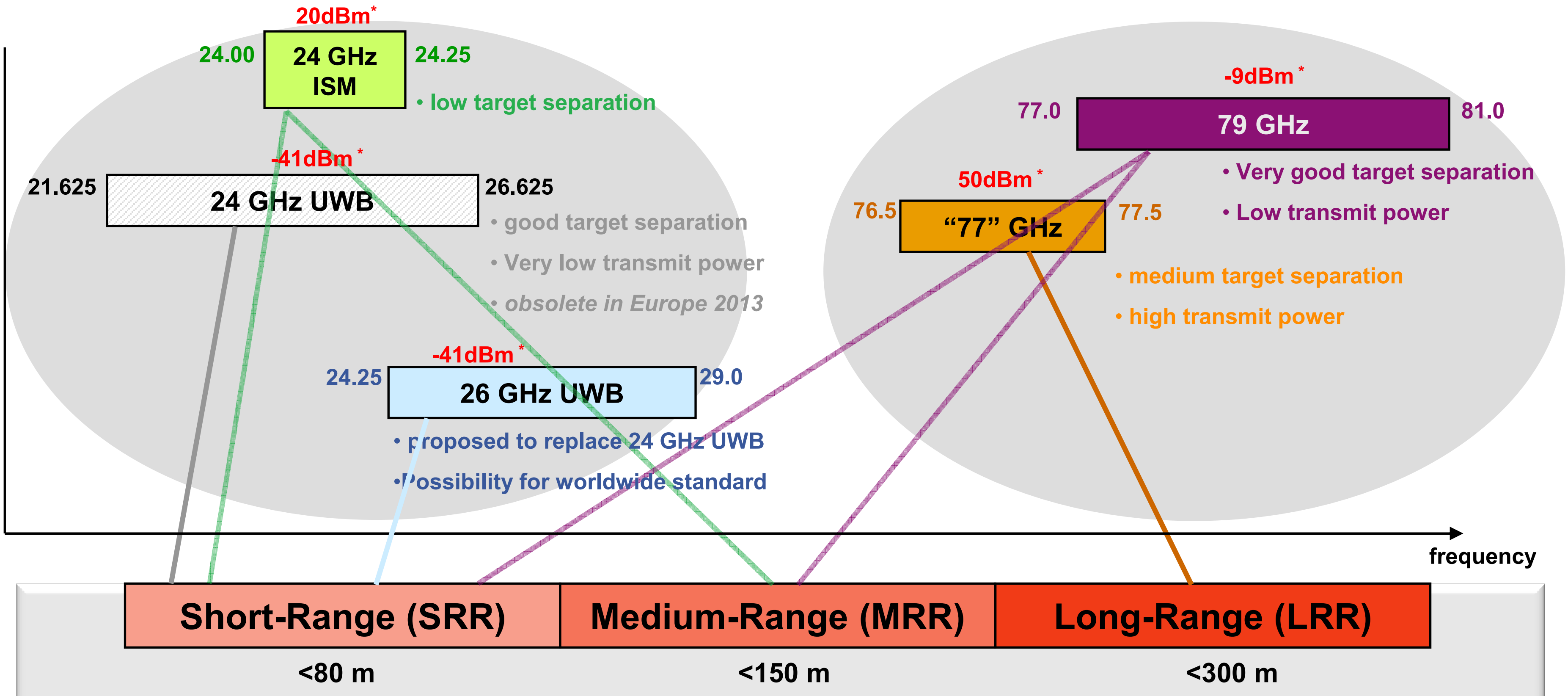
Method to notify the observer about remote metallic object, by using radio waves

Radar Frequency Bands: Limitations + Applications

- easy to package in plastic
- high integration level
- *reasonable cost*
- *large antenna 3x of 77GHz*

RF

- usually used as die, packing issue
- low integration level
- *high cost, yield*
- *small antenna, 1/3 of 24GHz*



Situation is Not Static!

New Techniques extending 24GHz to LRR and 77GHz to MRR/SRR

* e.i.r.p. equivalent isotropic radiated power

Radar Comparison

Type	Range			Target Resolution	System/ Antenna Size	MMIC cost	Outlook
	Short <80m	Medium <150m	Long <300m				
24GHz ISM	☑	☑	?	**low**	**Medium**	**Low** (integration possible; plastic pkg compatible)	**$50 sys cost today helping adoption in BSD and other near-range. SMS and others attempting LRR**
24GHz UWB	☑			**good**	**medium**	**Low** (integration possible; plastic pkg compatible)	**Obsolete in Europe >2013**
26GHz UWB	☑			**good**	**medium**	**Low** (integration possible; plastic pkg compatible)	**Not yet approved**
77GHz			☑	**medium**	**Low** (1/3 the size)	**High** (exotic materials; hard to integrate)	**Can cover SRR to LRR and is smallest form-factor; long-term, cost improvements to make more competitive**
79GHz	☑	☑		**Very good**	**Low** (1/3 the size)	**High** (ditto)	

Possible Combinations using system synergy

Type	Range			Target Resolution	System/ Antenna Size	MMIC cost
	Short <80m	Medium <150m	Long <300			
24GHz ISM 26GHz UWB	☑	☑	?	**Medium** distance dependent	**Medium**	**Low** (integration possible; plastic pkg compatible)
77GHz 79GHz	☑	☑	☑	**Good** distance dependent	**Low** (1/3 the size)	**High** (exotic materials; hard to integrate)

Outlook

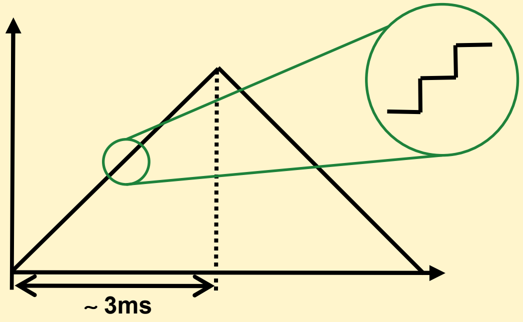
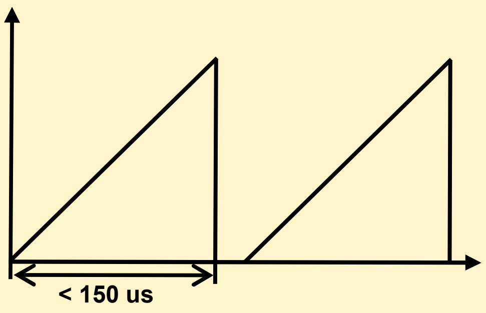
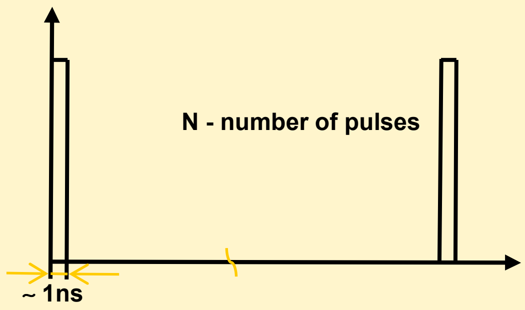
24/26GHz

- System cost will be further reduced
- LRR Performance and range will be improved but stays behind 77/79GHz
- Still dominate SRR applications, because of cost.

77/79GHz

- It will take several years to solve technical challenges.
- Integration level will improve and cost comes down, but stays above 24GHz
- The better LRR performance will solidify the position in ACC especially on high end cars

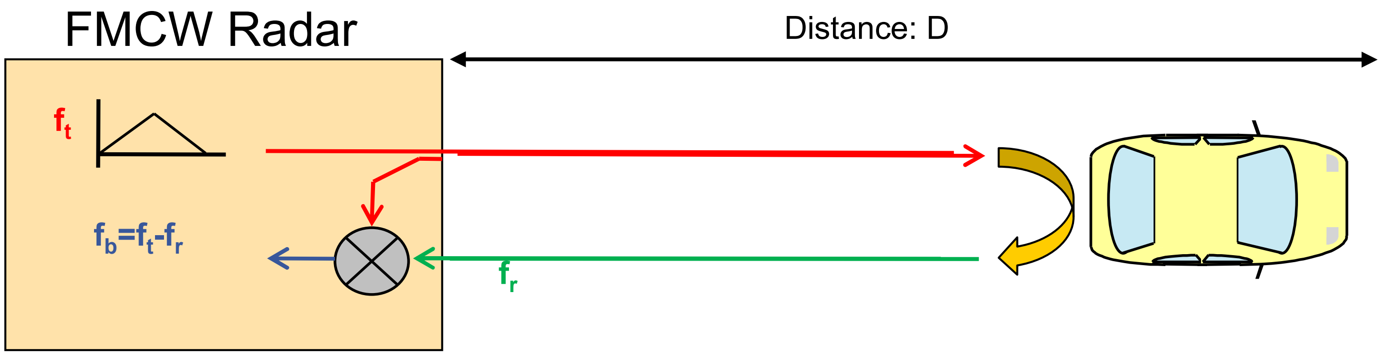
Radar Architectures in Automotive

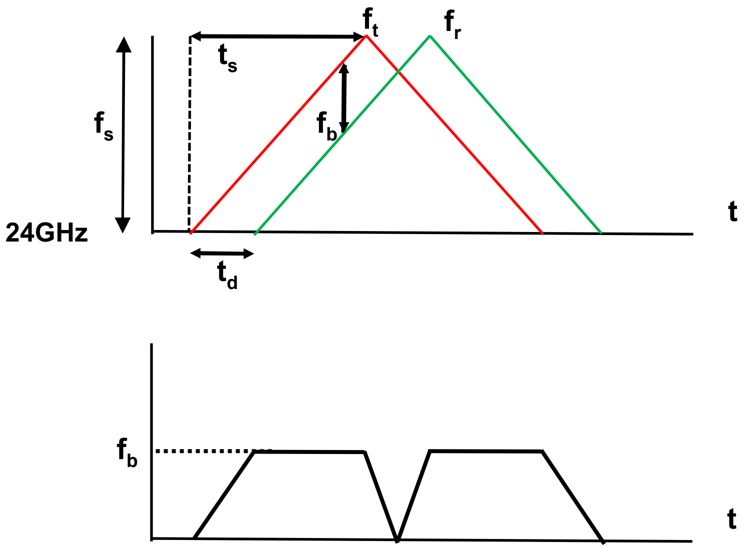
Automotive Radar		
FMCW		Pulse Doppler Radar
LSR-Low Speed Ramp	HSR-High Speed Ramp	Pulse Train
		
Doppler Frequency is usually determined through variable slopes and/or FSK modulation.	Increasing slope+ bandwidth makes Doppler Frequency negligibly, Velocity is measured by distance over time.	Velocity and distance are measure instantaneously.
Can work with limited bandwidth like 24GHz narrowband but is scalable to higher bandwidth too		Requires higher bandwidth, typically used in 24/26GHz UWB or 79GHZ

FMCW-RADAR

FREQUENCY MODULATED CONTINUES WAVE RADAR

FMCW Principle
(simplified without Doppler)





(1) $t_d = 2*D/c \rightarrow$ 1us at 150m

(2) $D = c*t_s*f_b/(f_s*2)$

(3) $BW = f_s*t_{dmax}/t_s$

(4) $BW = f_s*2*D_{max}/(c*t_s)$

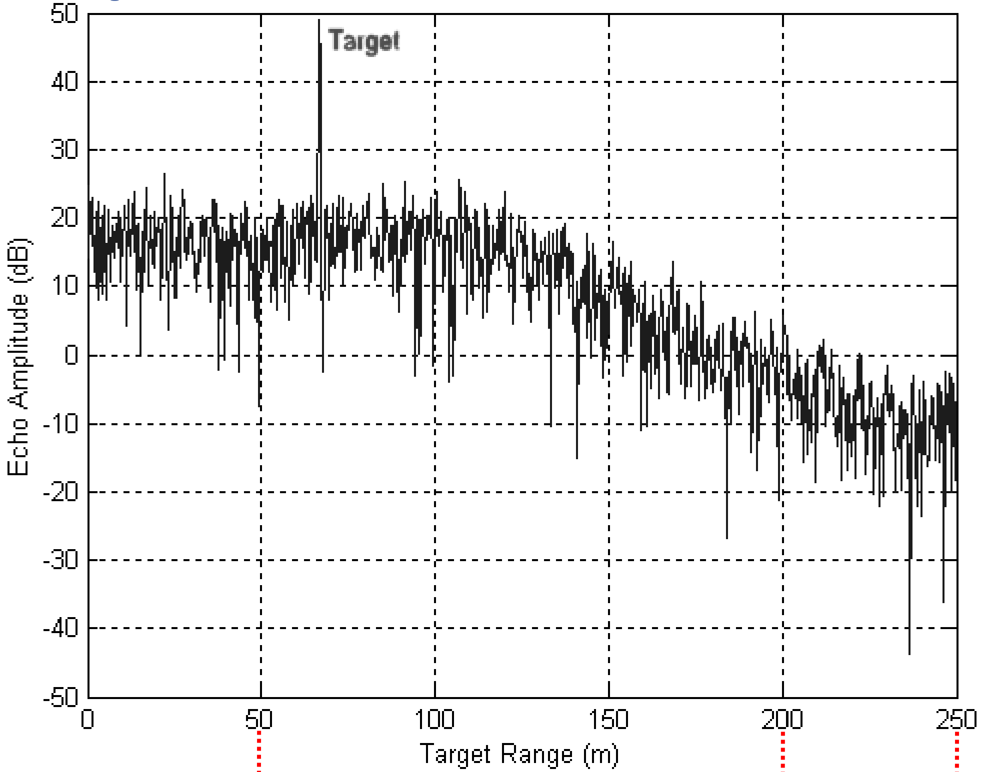
- f_t: Transmit Frequency
- f_r: Receive Frequency
- D: Distance
- t_d: Time of flight for D
- f_b: Beat Frequency
- f_s: Sweep Frequency
- t_s: Sweep Time
- C: Light Speed Constant

Example:

f_s = 200MHz
t_s = 2ms
t_{dmax} = 150m $\rightarrow$ Bandwidth BW=100KHz

ANALOG DEVICES

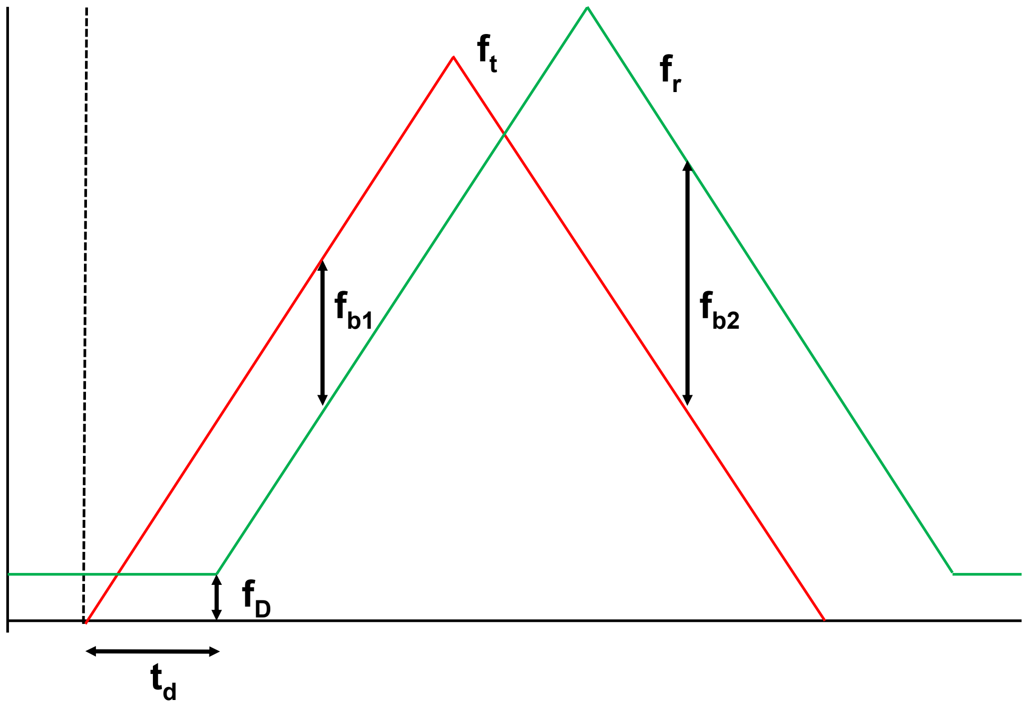
Baseband Example



Distance	50	100	150	200	250
Low Speed Ramp 200MHz@2ms	33KHz	66KHz	100KHz	133KHz	166KHz
High Speed Ramp 200MHz@20us	3.3MHz	6.6MHz	10MHz	13.3MHz	16.6MHz

Why using different ramp profiles?

FMCW with Doppler Shift



$$f_{b1} = f_b - f_D$$
$$f_{b2} = f_b + f_D$$

$$\rightarrow f_b = (f_{b1} + f_{b2})/2$$
$$\rightarrow f_D = (f_{b2} - f_{b1})/2$$

Doppler shift is eliminated/determined by triangular ramp with identical slope rate up and down

Doppler Shift to Baseband Frequency

Speed (km/h)	Carrier Frequencies	
	24GHz	76GHz
	Doppler Frequency (KHz)	
1	0.04	0.01
10	0.44	0.14
50	2.22	7.04
100	4.44	14.1
180	8.00	25.3

Distance	50	100	150	200	250
Low Speed Ramp 200MHz@2ms	33KHz 77%	66KHz 38%	100KHz 25%	133KHz 19%	166KHz 15%
Fast Ramp 200MHz@20us	3.3MHz 0.8%	6.6MHz 0.4%	10MHz 0.25%	13.3MHz 0,2%	16.6MHz 0,15%

This does not mean that the High Speed Ramp approach is better than the Low Speed Ramp approach, there are pros & cons for both systems.

Dynamic Range Requirements

Radar Equation

$$\frac{P_r}{P_t} = \frac{G^2 \cdot \lambda^2 \cdot \sigma_S}{(4\pi)^3 \cdot R^4}$$

- G = Antenna Gain (assumes G_t=G_r=G; i.e. same antenna used for Tx and Rx; ex. 31 dB)
- P_t and P_r = Transmit and receive power
- λ = wavelength of carrier frequency (ex. 76 GHz => 3.95mm)
- σ_S = Radar Cross Section (ex. 2m^2 for motorcycle)
- R = range (ex. maximum 150m; time of flight = 2R/c = 1µs)

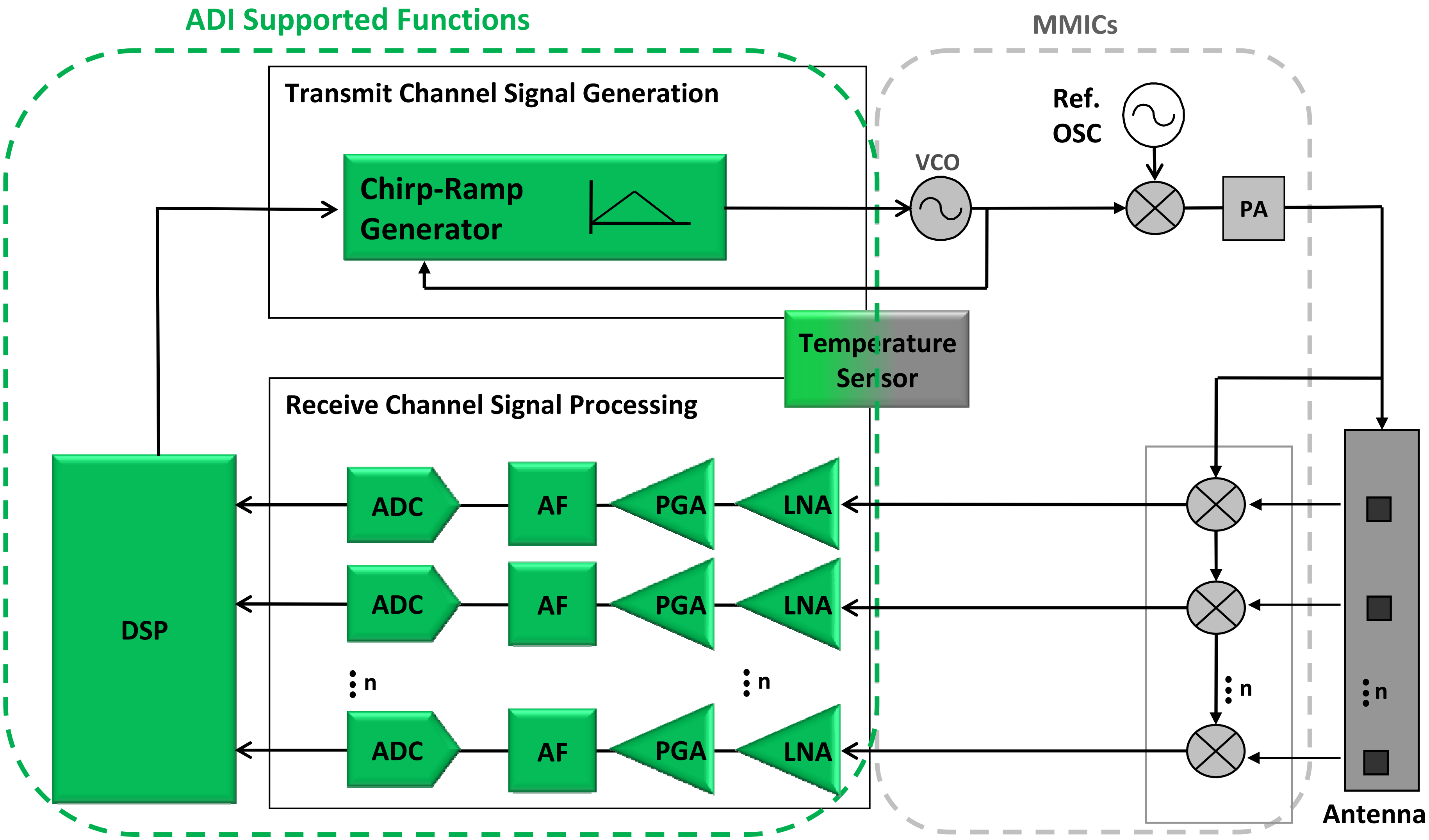
Dynamic Range

$$DR = 10 \bullet \log(\frac{P_{R2}}{P_{R1}}) = 10 \bullet \log(\frac{R1^4}{R2^4}) = 40 \bullet \log(\frac{R1}{R2})$$

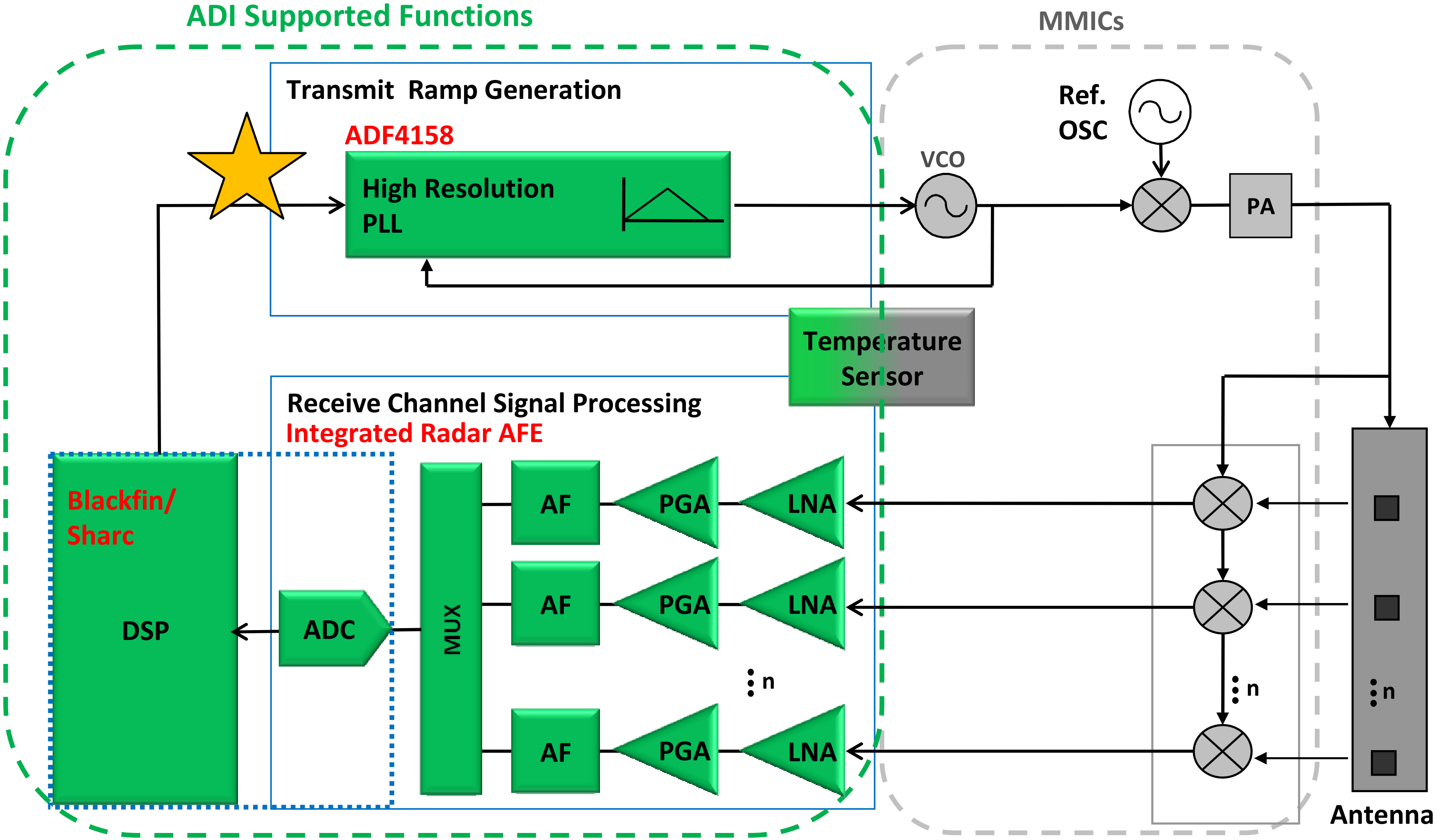
	Short Range	Short - Medium Range	Short - Long Range
R1 (m)	1	1	1
R2 (m)	50	150	300
DR [1)]	68dB	87dB	100dB

1) + fixed gain depended MMIC RF Level
+ certain resolution to detect and classify object
- attenuation of high pass filter at the input

FMCW RADAR
Signal Chain Representation



FMCW RADAR
Signal Chain Representation



ANALOG DEVICES

FMCW Radar Ramp Generation

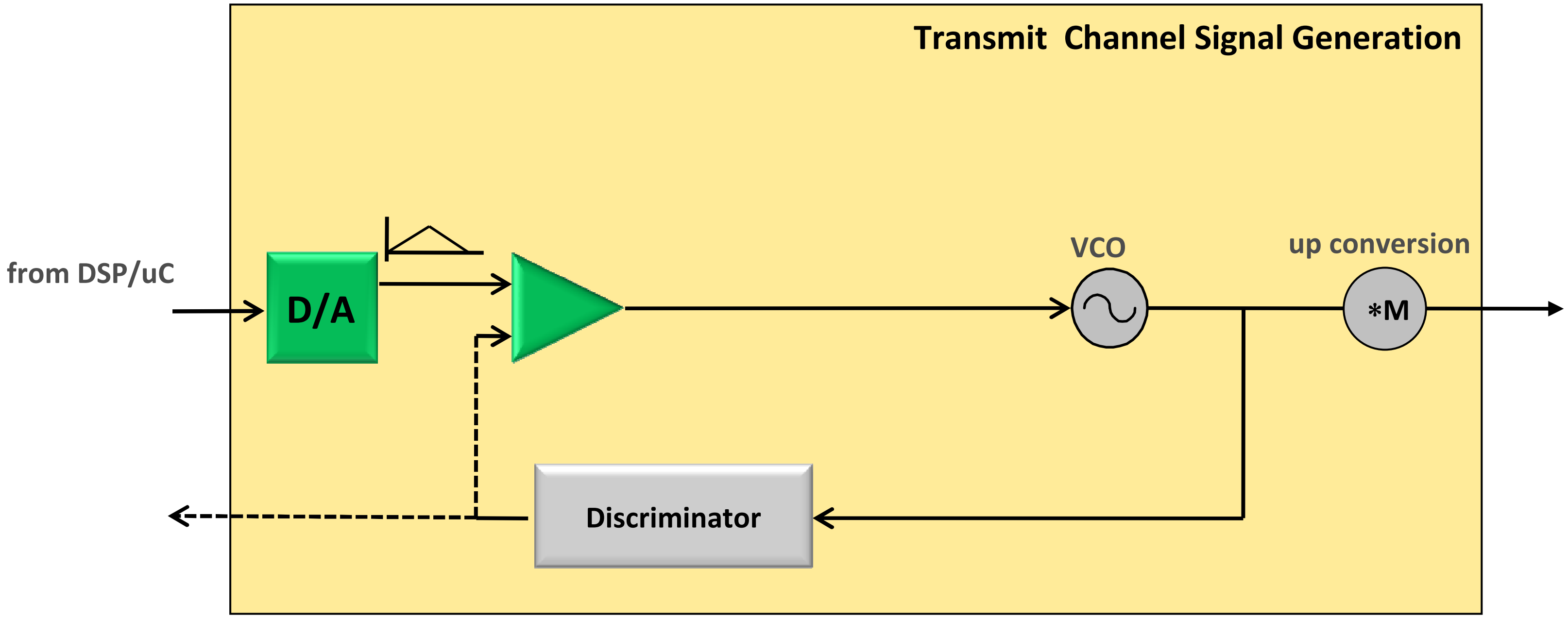
- FMCW Radar are used in a wide range of automotive applications and the system performance has been improved significantly over the last years.
  - Larger dynamic range, <0.5 to 300m
  - Wider Field of View
  - Better velocity, distance and angular resolution
  - Reliable target detection, separation and tracking
  - Faster response time

- Ramp generation is one of the key elements in the signal chain to achieve this system level performance.
  Unique and proprietary modulations schemes and ramp-timings have been developed set new challenges on the
  FMCW ramp generation

Transmit Ramp Generation
Key Design Objectives:

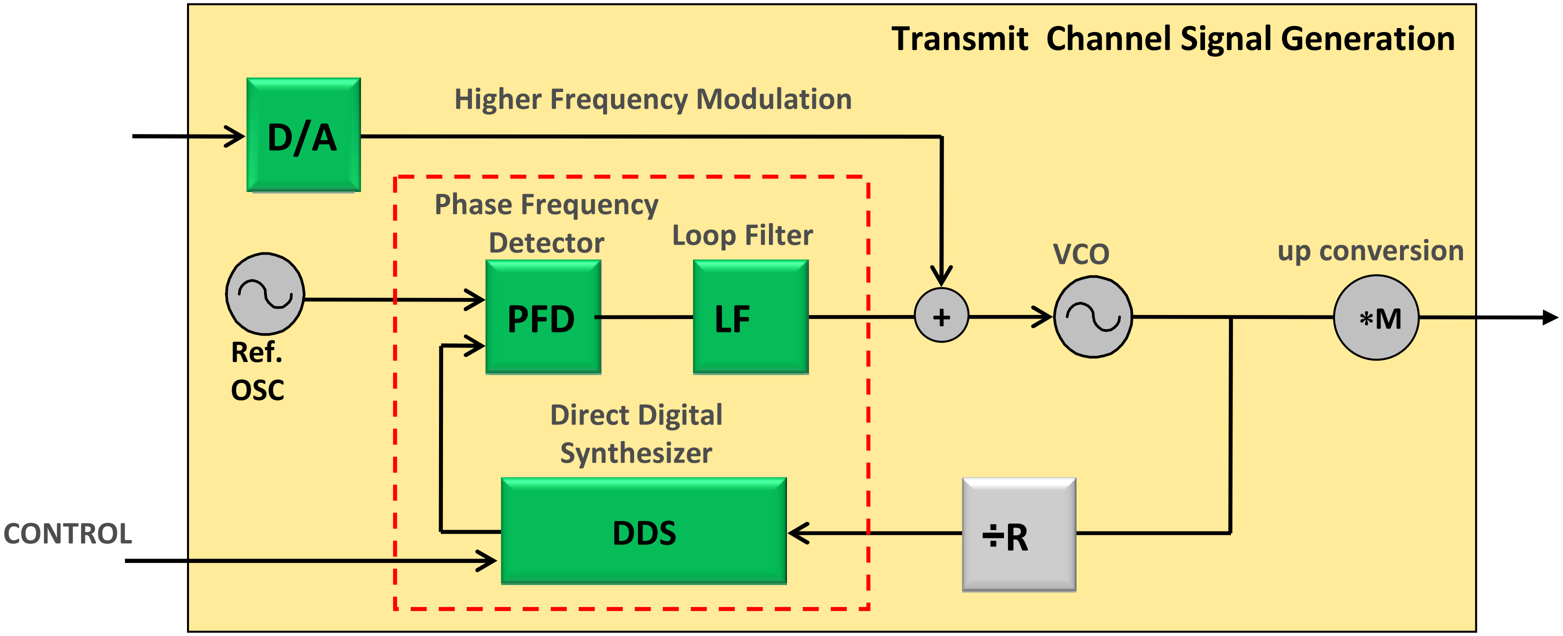
- Wide range of ramp profiles are used in automotive radar, ranging from triangular (variable slopes), saw tooth, FSK modulation and variable timing.
  → flexibility
- Linearity, low phase noise, high resolution and temperature stability have direct impact on system performance
  → performance
- Low power to reduce self heating, keep fuel consumption low
  → low power consumption
- Complex ramp functions might require significant system/ CPU overhead
  → self-contained ramp function
- And all above at reduced system cost
  → low cost

Ramp Generation Options
→ DAC



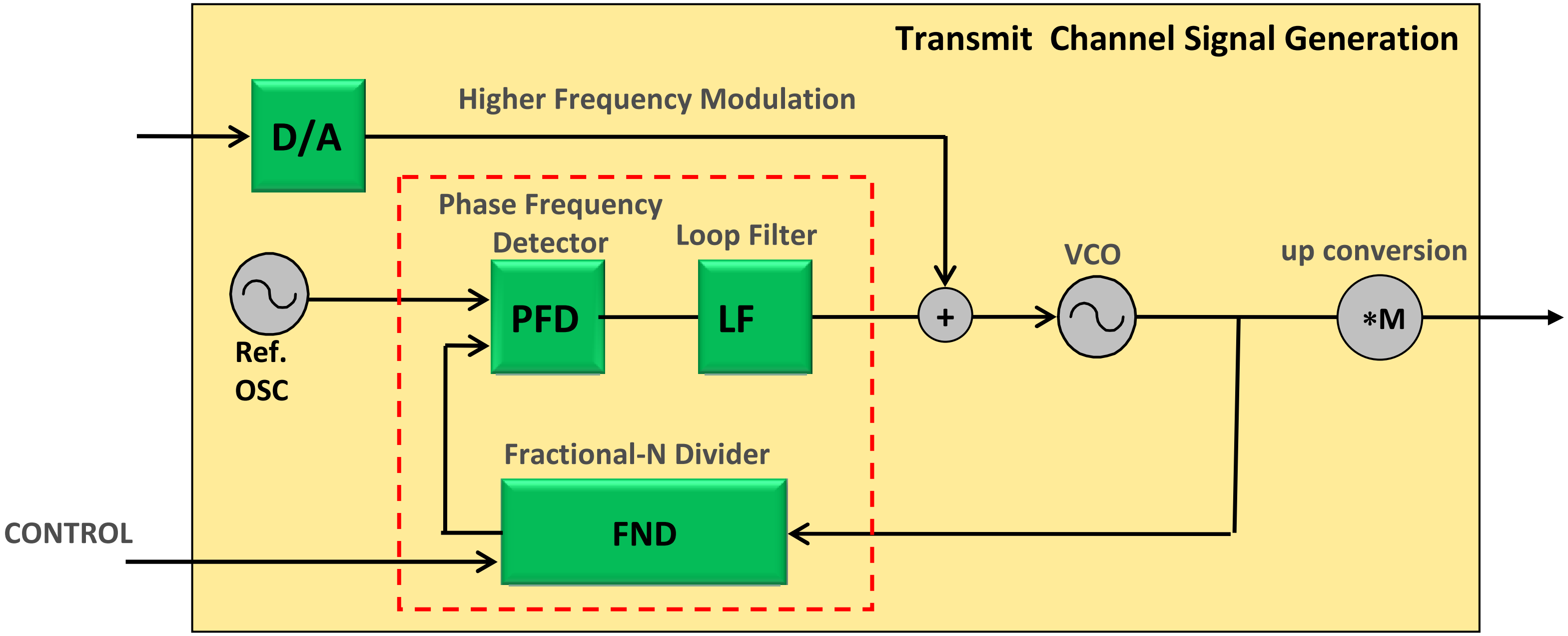
+ flexible ramp shape
+ very fast ramps possible
+ less spurs than PLL
- discriminator and look-up table needed
- usually higher system cost than PLL
- (additional MCU/DSP resources)

Ramp Generation Options
→ DDS and PLL



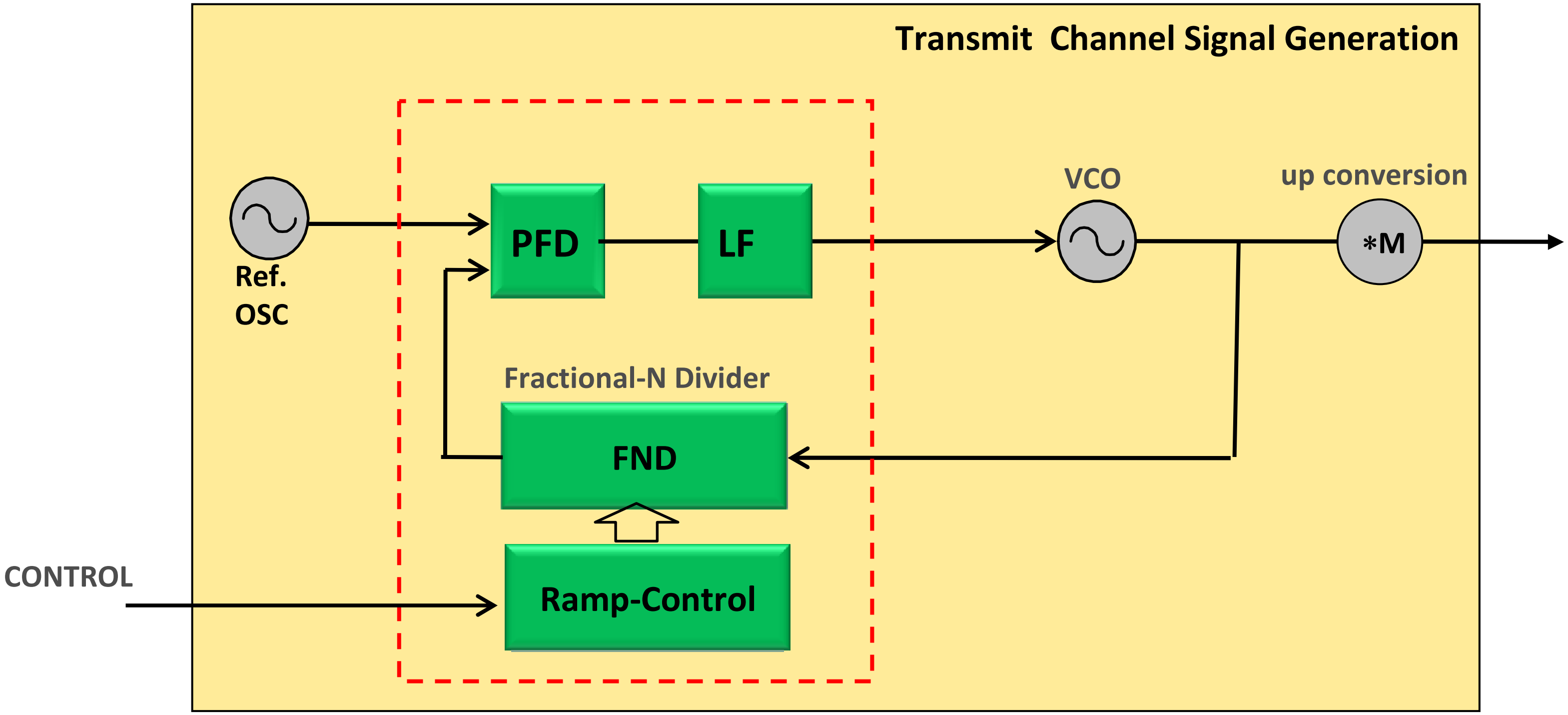
+ limited ramp speed
+ less spurs than PLL with FND
+ always linear, no correction for VCO needed
- higher cost
- higher power consumption
- additional DAC needed depending on ramp modulation scheme

Ramp Generation Options
→ PLL+DAC



+ any ramp speed generated.
- correction for VCO needed
- additional DAC needed depending on ramp modulation scheme

Ramp Generation Options
→ ADF4158



+ lower system cost
+ always linear, no correction for VCO needed
+ lower MCU/DSP interaction (especially ADF4158)

ADF4158: Direct Modulation/Waveform Generating 6GHz Fractional-N Frequency Synthesizer

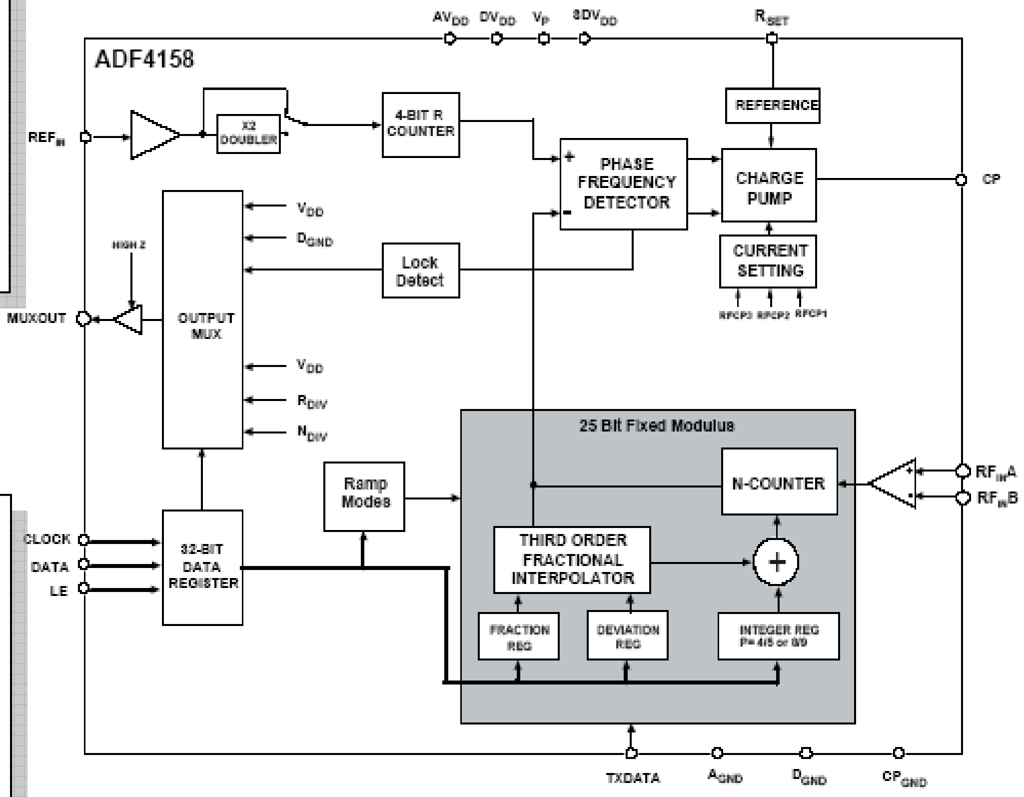
KEY SPECIFICATIONS

- 500MHz – 6000MHz Range
- 25 bit divider modulus
- 32MHz PFD maximum frequency
- Normalised PN Floor = -207dBc/Hz
- FSK deviation up to 32MHz

FEATURES

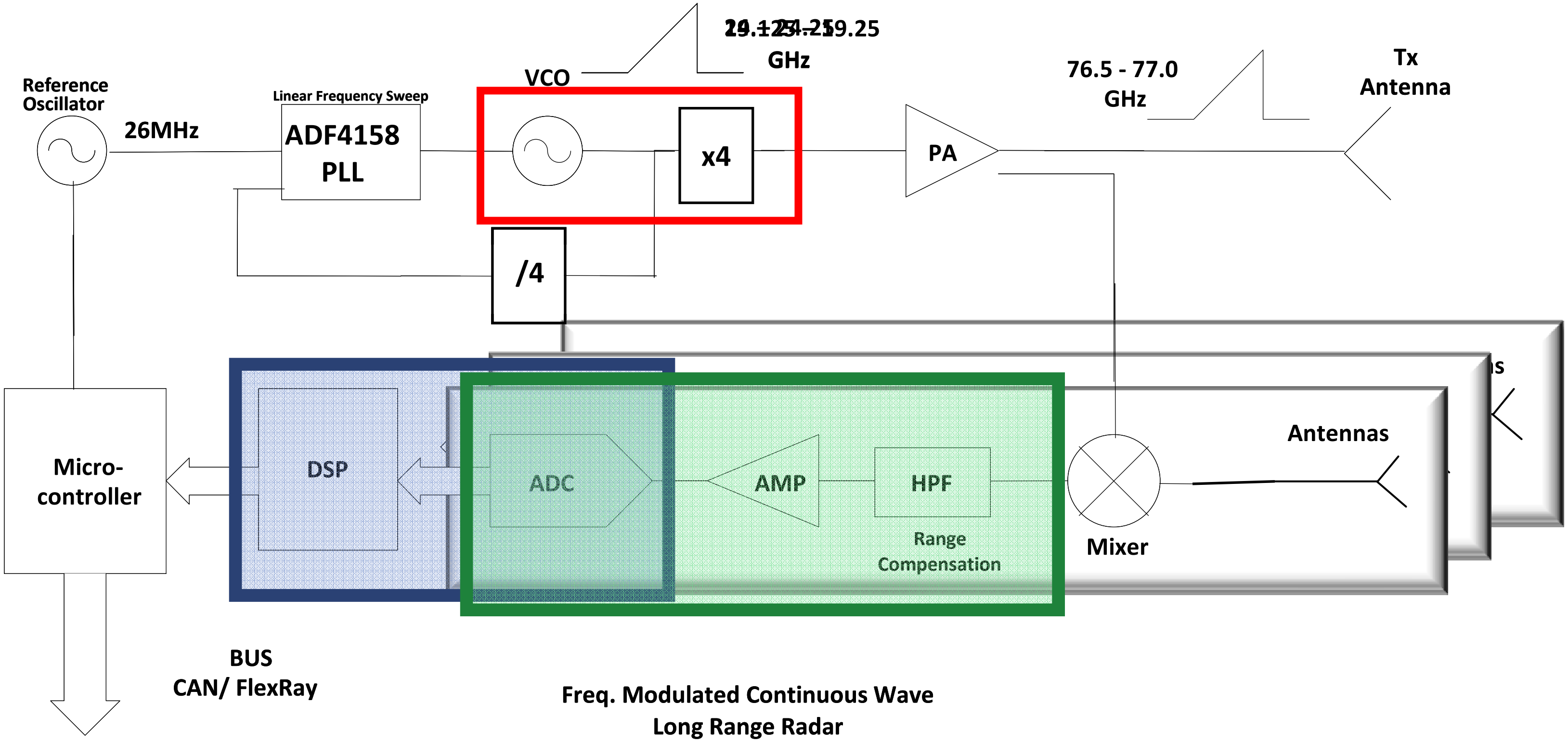
- Sub-1Hz frequency resolution
- FSK and PSK modulation capability
- Generates highly linear sawtooth and triangluar waveforms
- Cycle slip reduction for fast locktimes
- 24-LFCSP (4mm x 4mm)

FUNCTIONAL BLOCK DIAGRAM



ANALOG DEVICES

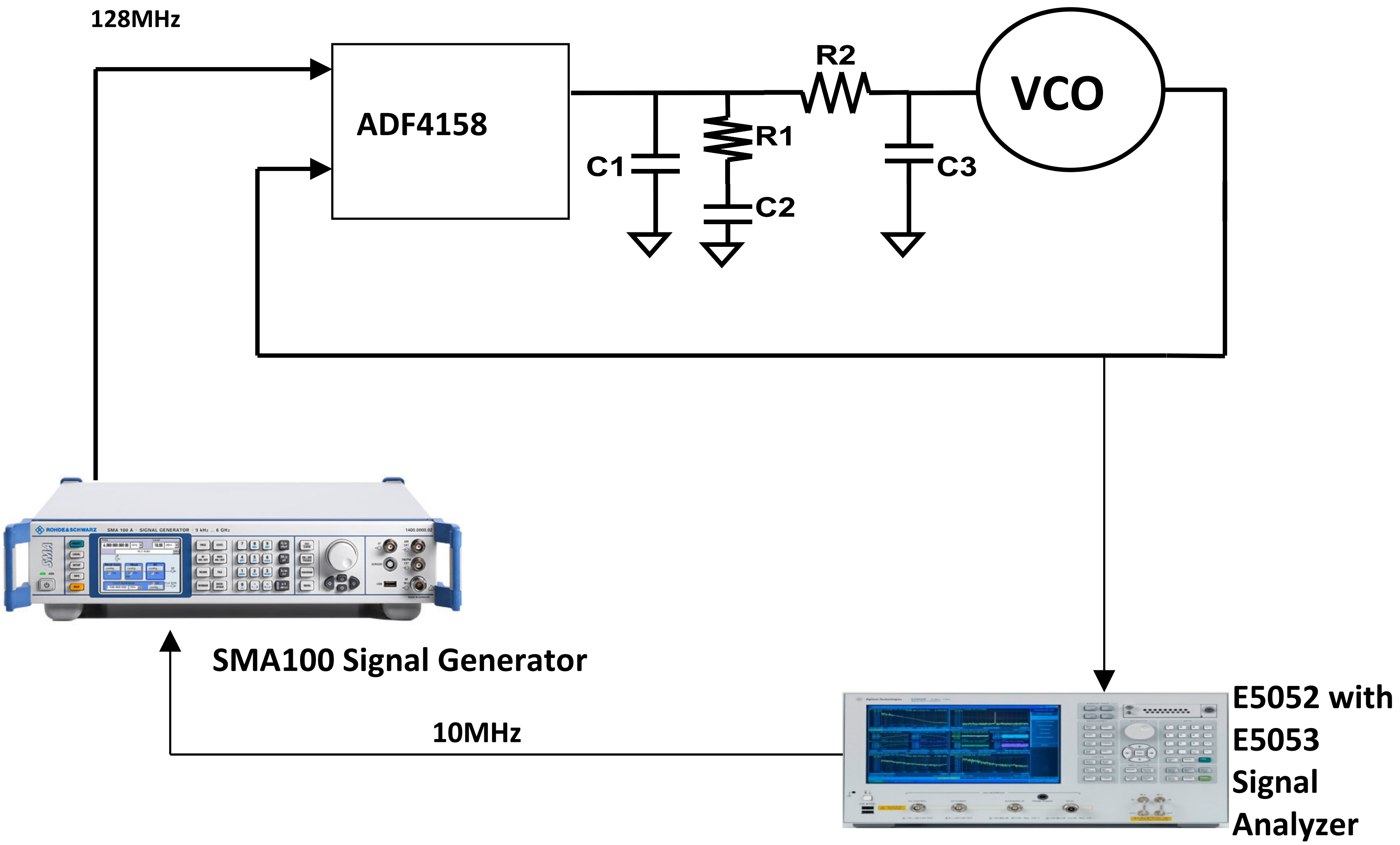
FMCW Radar Using High Resolution ADF4158 Ramp Generator



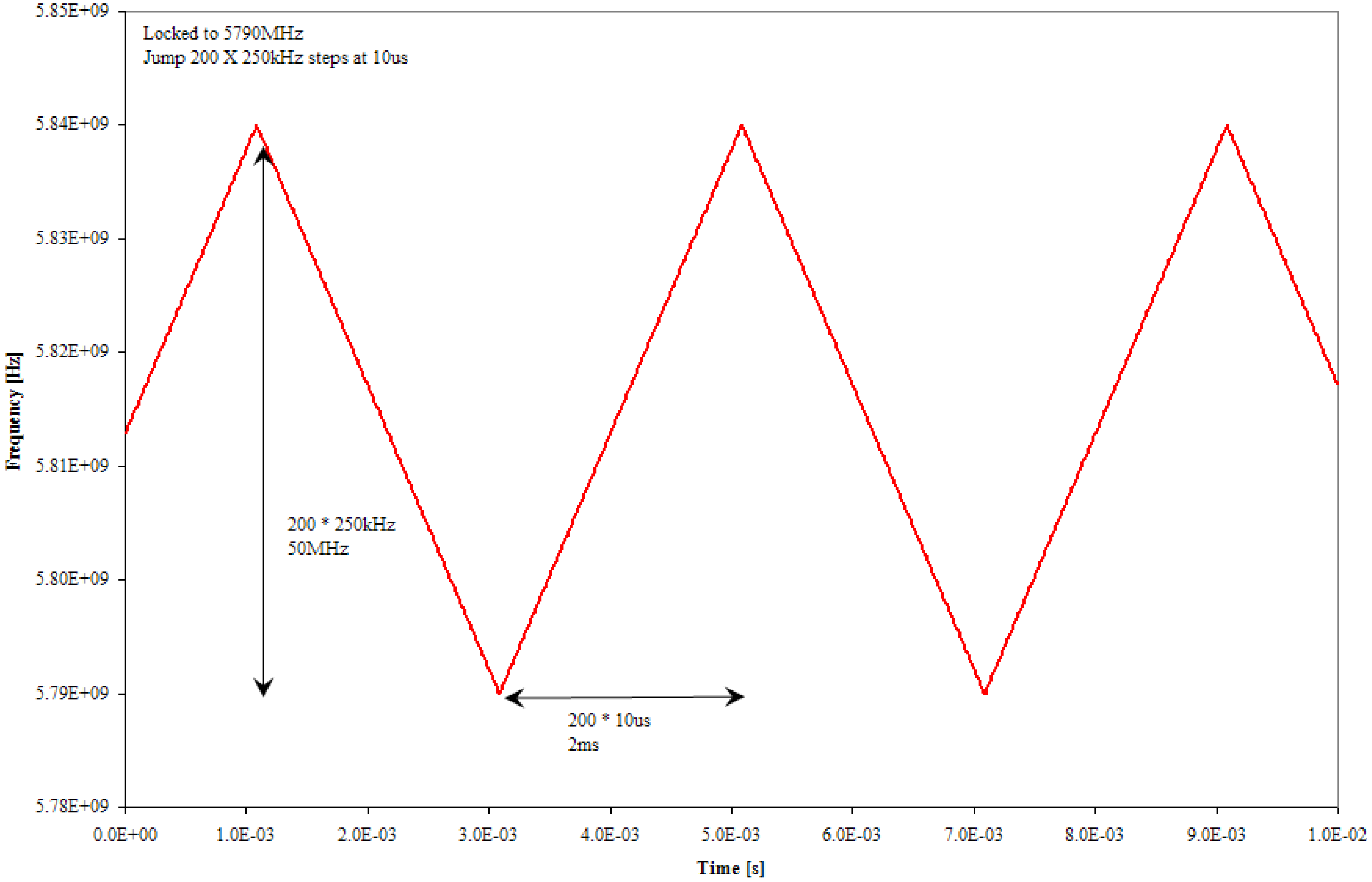
Freq. Modulated Continuous Wave
Long Range Radar

ANALOG DEVICES

Measurement Setup

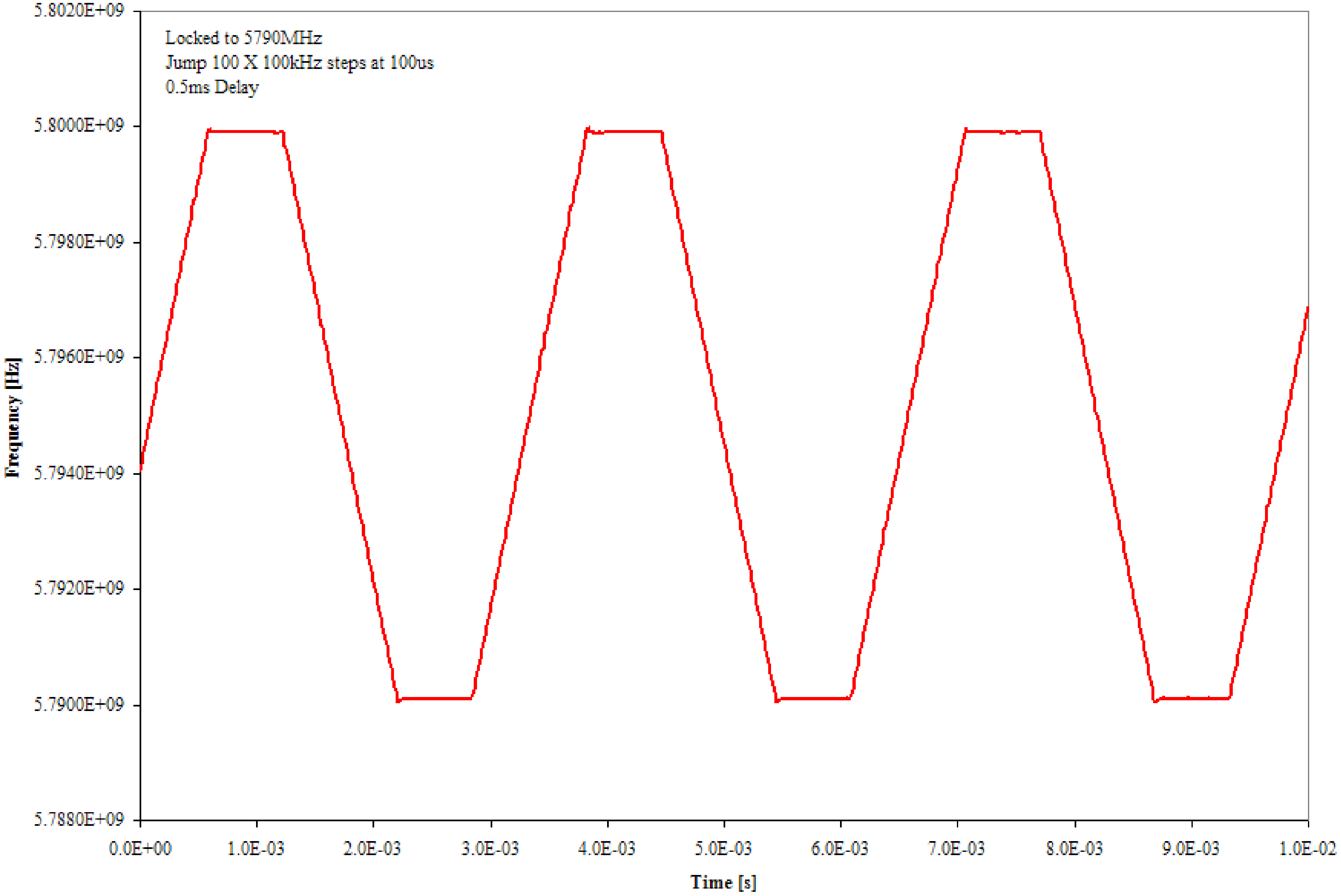


Basic Triangular ramp

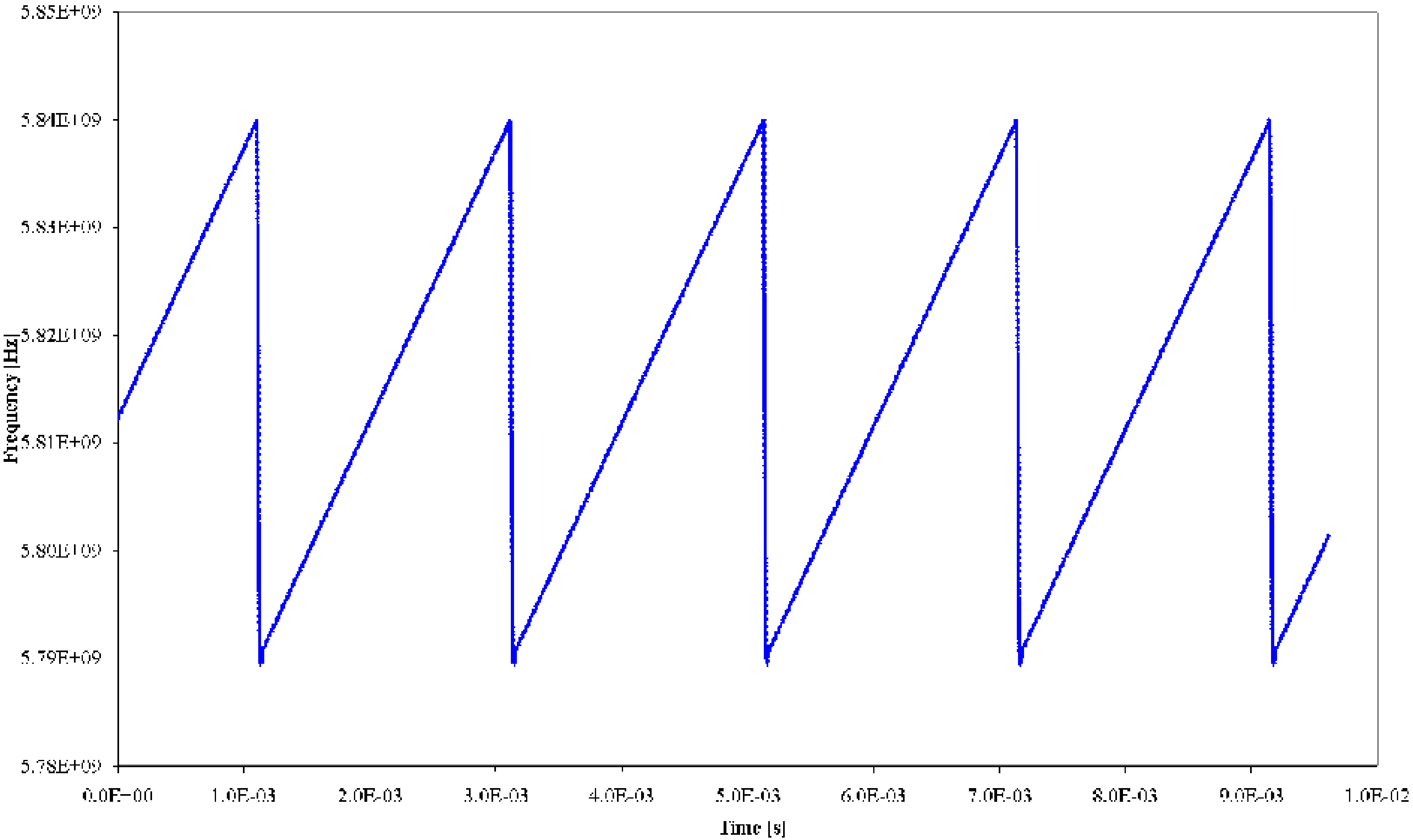


ANALOG DEVICES

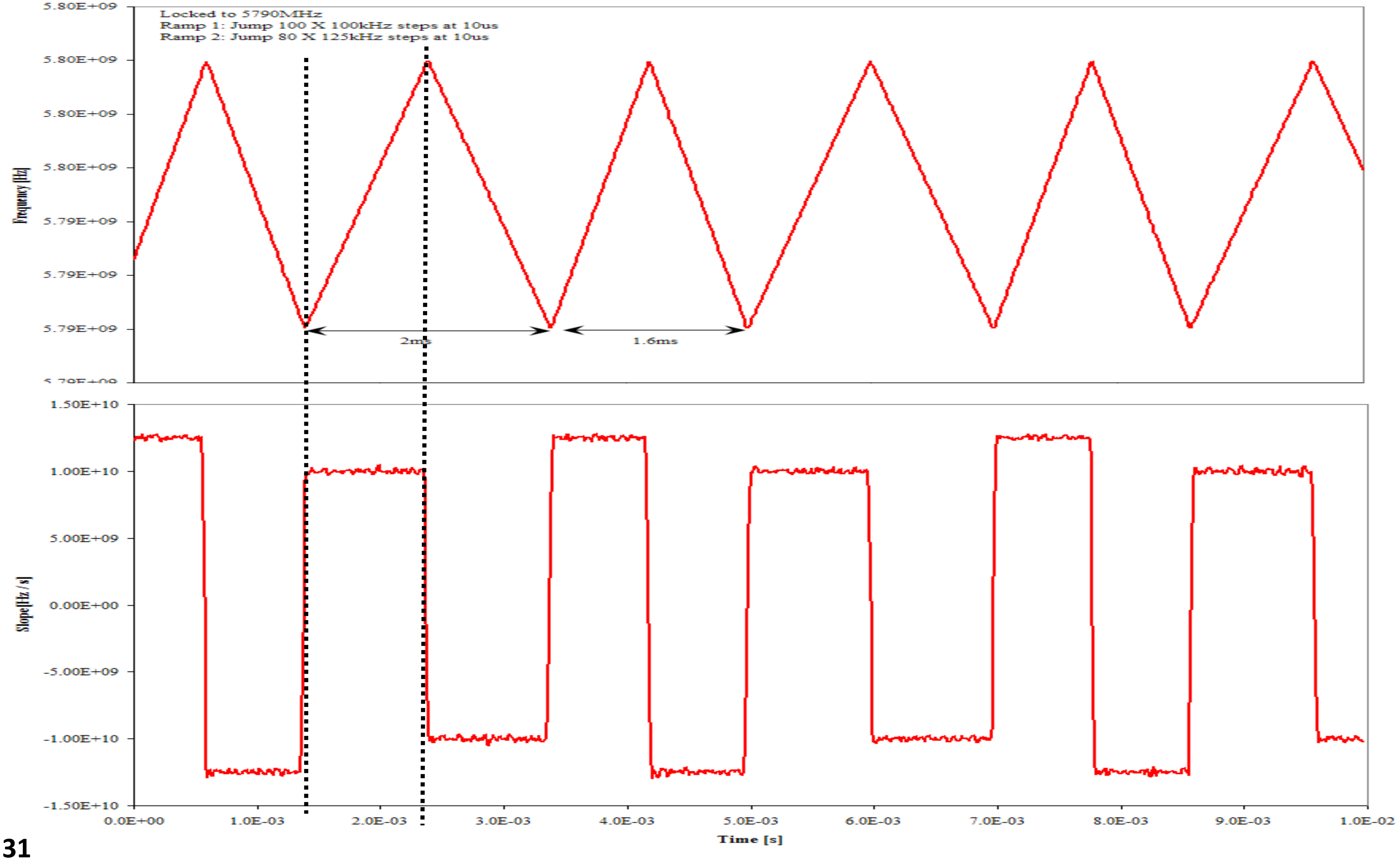
Triangular ramp with delay



Saw tooth ramp

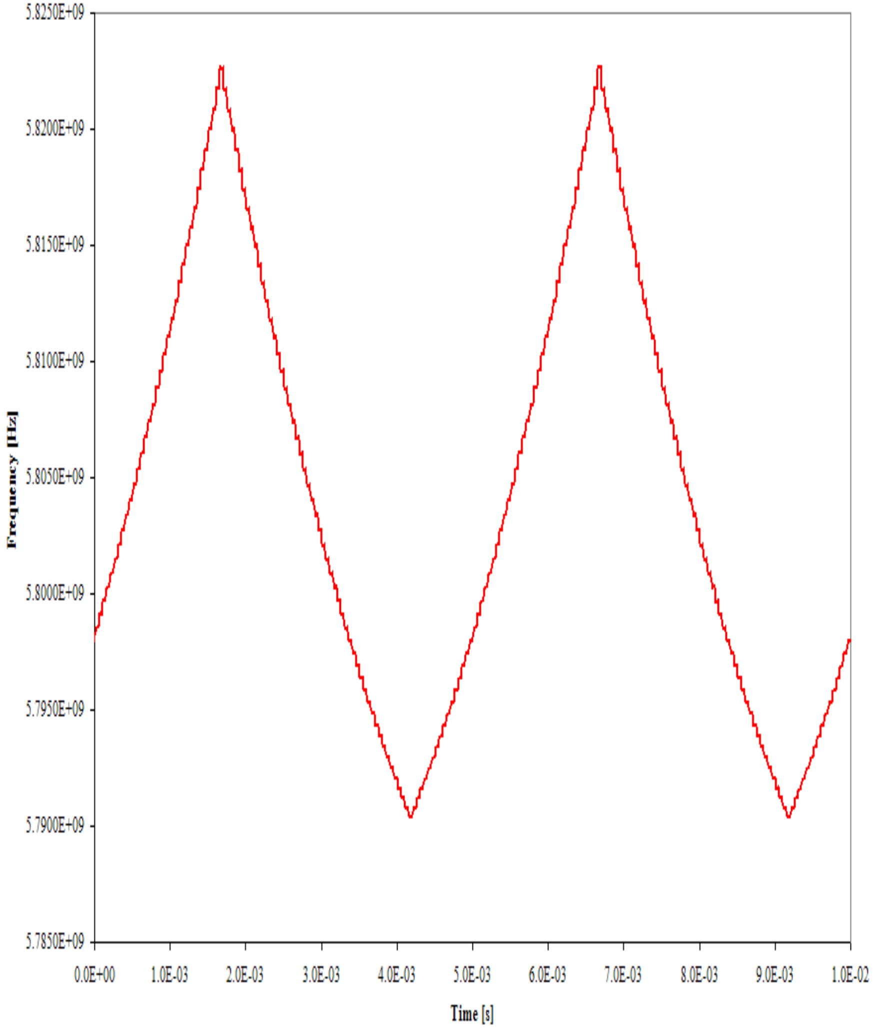


Multiple slope ramps

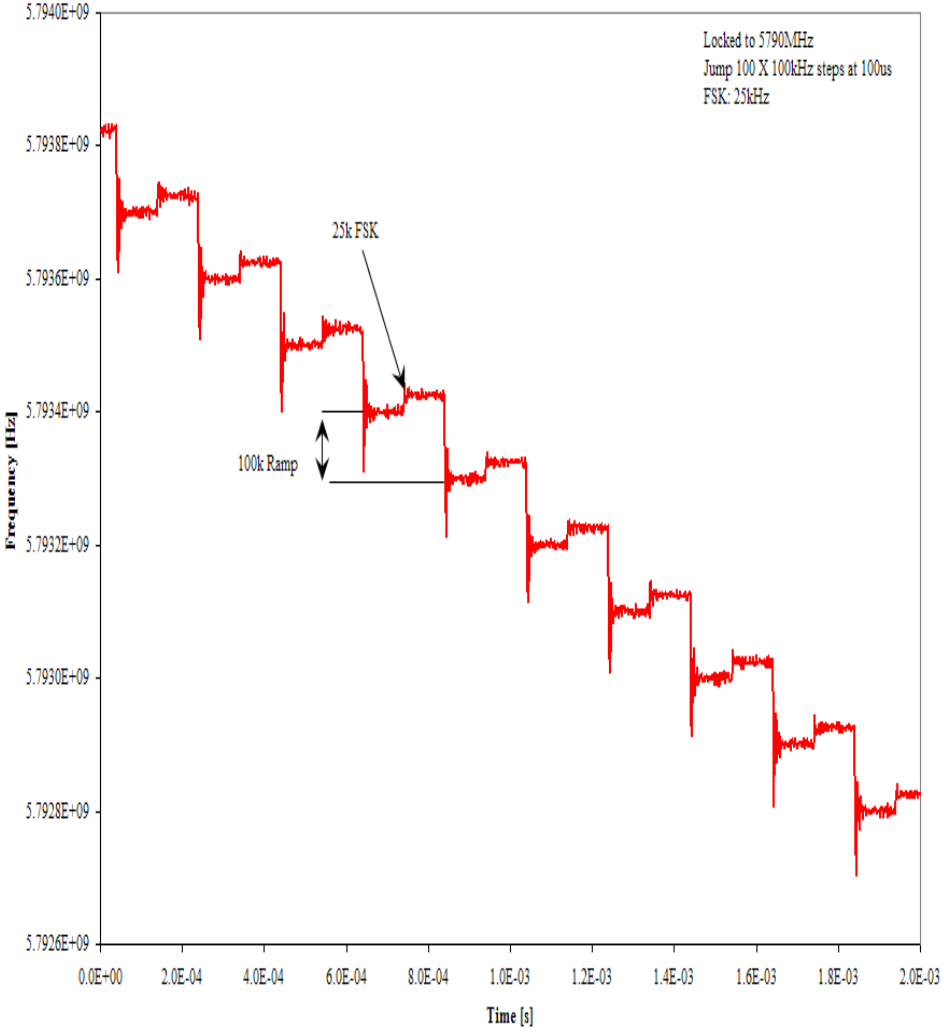


Other ramp function

Parabolic ramp



Linear ramp + FSK



Conclusions

- Innovative architectures and components are being developed to enable improved cost/performance optimization in automotive radar systems
- Precise ramp generation is critical in FMCW applications to achieve the desired target resolution.
- Advancements in PLL technology now enable affordable capabilities such as multi slope ramps or FSK modulation superimpose to the ramp.
- Lower-Cost, Higher Performance systems will evolve through optimized partitioning of high-volume standard products from Communications Applications coupled with specialized Automotive ASICs

Acknowledgements

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