FMCW Radar in Automotive Applications
Technology Overview & Testing

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GNSS / eCall
- R&S®SMBV
- R&S®CMW

GNSS Simulation Solutions

EMC
- R&S®TS9982
- R&S®SMB100A
- R&S®FSW
- R&S®NRP
- R&S®ARTS
- R&S®SMW
- R&S®ZNB
- R&S®SMZ

Car2Car / Car2X
- R&S®ITS100
- R&S®CMW
- R&S®FSW
- R&S®FSWP

Communication and Interference

Automotive Radar Solutions
- R&S®FSW
- R&S®ARTS
- R&S®SMW
- R&S®ZNB
- R&S®SMZ

Verification of Driver Assistance Systems

Audio / Video / Infotainment
- R&S®BTC
- R&S®SFE100
- R&S®CMW

Evaluate the quality of infotainment systems

Automotive Bus Systems
- R&S®RTM
- R&S®RTO
- R&S®RTH

Bus analysis with dedicated options for CAN, BroadR-Reach...

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FMCW Radar in Automotive Applications
Today’s material

Radar Fundamental Concepts

FMCW Automotive Radar

R&S Test Solutions for Automotive Radar
Radar fundamentals
Radar use cases

Measurement of…

- Range *
- Velocity *
- Target size (RCS)
- Azimuth angle
- Elevation angle

It’s all the same physics but the mathematical techniques employed may be different.

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Beam Steering

Tracking

Weather

Imaging

Automotive

Speed enforcement
Frequencies used in automotive radar

- Various millimeter wave frequency bands in use today
  - 24 GHz
  - 77 GHz
  - 79 GHz

- Why 24 GHz?
  - Temporary band (at least in Europe).
  - Disadvantage of having bandwidth limitations of 200 MHz bandwidth due to other usage of the ISM spectrum.

- Why 77 and 79 GHz?
  - Higher channel bandwidth available offers better range resolution.
  - Higher frequency means better velocity resolution & smaller components.
Uniqueness of 24 & 77 GHz frequencies

While a high attenuation might be a disadvantage for many applications, it does allow frequency reuse within very short distances.

In fact, the attenuation limits the distance of mm wave radar which, in the case of having thousands of cars on the road using their radars simultaneously, is a good thing.
Automotive specific radar applications
Pulsed or FMCW?
Pulsed vs. FMCW

Which is a better fit for automotive radar?
Range measurement - Pulsed radar

\[ \text{Range} = \text{Rate} \times \text{Time} \]

\[ \text{Range} = c \times \frac{\tau}{2} \]

\( c = \text{speed of light} = 299,792,458 \text{ m/s} \)

Easy to range using pulsed radar as there is always a starting point
Range measurement - FMCW radar

Range = Rate * Time

Range = c * \frac{\tau}{2}

How to determine range when there is no starting point? It’s continuous!
Range resolution measurement – Pulsed radar

Sufficient range resolution

Insufficient range resolution

Range resolution determined by adjusting pulse width

\[ \Delta \text{Range} = c \times \frac{W}{2} \]
Range resolution measurement - FMCW radar

How to determine $\Delta R$ when there is no pulse width? *It’s continuous!*
How computationally intensive? – Pulsed vs. FMCW

Send out a pulse and listen for a reflection

Constantly transmit and listen, while doing a lot of mathematical calculation to make sense of it all
### Best fit for automotive radar?

<table>
<thead>
<tr>
<th></th>
<th>Pulsed</th>
<th>FMCW</th>
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<tbody>
<tr>
<td>Ranging</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Required</td>
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<td>✗</td>
</tr>
<tr>
<td>computational power</td>
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</tbody>
</table>

And the Winner is... FMCW!
Computational power is relatively inexpensive

Faster processors make the real-time complex math required for FMCW possible. Lower cost of these processors makes the distribution of many of them around the perimeter of the automobile more realizable.
The downside of pulsed radar

Pulsed Radar

- Wide bandwidth
- Higher power requirements
- Can't listen while transmit
- Expensive

FMCW Radar

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FMCW automotive radar

Adaptive Cruise Control

Emergency Braking

Pedestrian Detection

Collision Avoidance

Lane Departure Warning

Traffic Sign Recognition

Cross Traffic Alert

Surround View

Blind Spot Detection

Rear Collision Warning

Park Assist

Park Assistance/Surround View

Long-Range Radar

LIDAR

Camera

Short-/Medium Range Radar

Ultrasound
**Static** target at a certain range $R$

- Range measurement: FMCW radar
- $v_{\text{car}} = 0 \text{ m/s}$
- $v_t = 0 \text{ m/s}$

Diagram:
- Transmit Signal
- Receive Signal
- $B_w$
- $f_T$
- $f_B$
- $T_{\text{CPI}}$
- $\tau$
- Measured
Range measurement - FMCW radar

\[ R = \frac{c}{2} \times f_B \times T_{CPI} \]

Range determined by beat frequency

\[ f_B = \frac{2}{c} \times \frac{B_w}{T_{cpi}} \times R \]

Because this beat frequency refers to the range contribution it’s often referred to as \( f_R \)

\[ f_B = \frac{\tau}{B_w} \times T_{CPI} \]

Solving for \( \tau \)

Plug \( \tau \) into pulsed range equation

\[ s(t) \]

\[ f(t) \]

Transmit Signal
Receive Signal

\[ s(t) \]

\[ f(t) \]

Transmit Signal
Receive Signal

\[ \text{Range} = \frac{c}{2} \times \tau \]

\[ T_r \]

\[ T_p \]

\[ T_{CPI} \]

\[ t \]
Let’s add some velocity to the picture

The Doppler effect, or Doppler shift, is named after the Austrian physicist Christian Doppler (1803-53)
Doppler shift is a measure of radial velocity

- What is Doppler?
  - A perceived wavelength shift taking place between a source and listener.
Range and velocity* measurement

A single **moving** target at a certain range \( R \)

\[
f(t) = B_w \left( \frac{f_D}{T_{CPI}} \right) \]

\[
f_D \text{ is the Doppler shift. Note it is not due to range!}
\]

\[
f_{B1} = f_R + f_D
\]

\[
f_{B1} = \frac{2 B_w}{c T_{CPI}} R - \frac{2}{\lambda} * v_t
\]

We now have **one** equation with **two** unknowns including \( R \) and \( v_t \). Therefore it cannot be solved in its present state. **What's needed is a second measurement.**
**Range and velocity measurement**

- Second transmitted slope

\[
\begin{align*}
  f_{B1} &= \frac{2 B_w}{c T_{CPI}} R - \frac{2}{\lambda} v_t \\
  f_{B2} &= -\frac{2 B_w}{c T_{CPI}} R - \frac{2}{\lambda} v_t
\end{align*}
\]

Now we have two equations and two unknowns, R and \( v_t \).

**Therefore we can now solve for both R and \( v_t \).**
What about 2 targets?

- Transmit Signal
- Receive Signal

$f(t)$

$B_w$

$f_{D}$

$f_{B1}$

$f_{B2}$

$t$

$T_{CPI}$

$2 \cdot T_{CPI}$

$f_{dev,1}$

$f_{dev,2}$

$f_{B3}$

$v_{car} = 0 \text{ m/s}$

$v_i \neq 0 \text{ m/s}$

Multiple Targets
Measurement issues with FMCW

Taking a closer look we can observe what’s important for the signal generation of the transmit signal.

Linearity of chirp
Oscillations change crossover points
Other waveforms ever needed?

Chirp Sequence

MFSK
Chirp sequence waveform

- Each chirp has its own beat frequency.
- Very short chirps so $f_D$ can be ignored.
- Chirp length much shorter than entire CPI.
- Doppler determined by *measure phase difference* between these short chirps.
- Works for multiple targets over one CPI.

\[
f_B = \frac{2B_w}{cT_{chirp}} R - \frac{2}{c} \varphi_r
\]

\[
f_B = \frac{2B_w}{cT_{chirp}} R = f_R
\]
Chirp sequence

FFT

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Measurement issues with a chirp sequence

- Linearity
- Statistics
  - Timing
  - Phase
  - Repeatability
Multi-frequency shift keying (MFSK) waveform

- It’s FMCW with a small twist
  - Same CPI, same Bw and same slope.
  - But using two frequency shifted (MFSK) transmit signals
- This technique allows us to measure $f_B$ and $\Delta \phi$ between $f_B$

\[
f_B = f_{B1} = f_{B2}
\]

\[
f_B = -\frac{2}{\lambda} v_r - \frac{2f_{dev}}{cT_{CPI}} R
\]

\[
\Delta \phi = \frac{4\pi T_B}{\lambda} v_r - \frac{4f_{Shift}}{c} R
\]

2 equations ($f_B$ and $\Delta \phi$) and 2 unknowns.
We can solve for velocity and range.
Parameters to be measured
• Shift frequency
• Timing
• Linearity
Test & measurement tools for the lab

**ARTS** - Automotive Radar Target Simulator
- Real-time simulation of up to four targets

**FSW** — Signal & Spectrum Analyzer
- FSW-K60/K60C/K60H Transient Measurements
- 160/320/500/2000 MHz Analysis Bandwidth*
ARTS – Automotive Radar Target Simulator

- Operating at 24 and 77/79 GHz radar bands
- Simulates range, Doppler and RCS
- Up to 1000 MHz bandwidth
- Delay Range: 9m – 2400m  
  step size: 6cm
- Speed Range: 0km/h – 700km/h  
  step size: < 4mm/s

It modifies the original radar transmission
24 GHz Bistatic

77 GHz Bistatic
The real world needs to be simulated realistically

- target 1
- Possible location
- Distance / Delay
- Speed / Doppler

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Advantages of ARTS

- Reduces size of needed chamber.
- Simulates targets in non-static environments.
- Simulates various target sizes (user adjustable).
- Simulates up to 4 targets.
- Fast with updates every millisecond.
- Programmable.
FSW – Signal & Spectrum Analyzer

- Various models up to 85 GHz
- BW up to 500 MHz internally
- BW extension up to 2 GHz through the use of external R&S RTO digital scope
- Transient & chirp analysis
- Wide dynamic range
Specific FSW Measurements

- Spectrum
- Spectrogram (waterfall)
- Frequency vs. time
- Amplitude vs. time
- Phase vs. time
- Full captured signal
  - Or selected region
  - Or detected chirp
- Chirp and linearity analysis
- Pulsed or FMCW chirps
- Chirp rate, deviation from linearity ramp
- Chirp states
- Chirp tabular results
- Long term statistics
FSW Transient Analysis Screen Shots

Analyze the Full spectrogram of the signal in waterfall view.

Analyze the chirp in an intuitive time-frequency plot.

Check the frequency deviation of the chirp at each time instant.

Summary table with critical chirp specifications.
FSWP – Phase Noise Analyzer

- Various models up to 50 GHz
- Measure spectral purity of signal sources such as synthesizers and VCOs
- Extremely low phase noise
- Very fast measurements
- Can be upgraded to a signal and spectrum analyzer
Other fun toys to test radar...

- Frequency multipliers
- Harmonic mixers
- Vector network analyzers
- Wideband vector signal generator
Questions?

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