Chapter 7: Radar Receiver

Receiver Types

- **Superregenerative receiver**
  - A single tube is used for the RF amplifier in RX and TX sources.
  - Advantages: Simplicity and low cost
  - Disadvantages: gain instability, poor selectivity, high receiver noise level

- **Crystal Video Receiver**
  - Advantages: Simplicity and low cost
  - Disadvantages: Poor sensitivity (No RF amplifier filter effect), Poor selectivity, poor pulse shape of video amplifier
  - 30 ~ 40dB loss than those achievable in Superheterodyne receivers.

- **TRF Receiver**
  - Add a RF amplifier prior to the detector in the Crystal Video Receiver
  - Improve sensitivity (reduce noise produced by the detector) and selectivity (RF amp. filtering), Reduce the video gain

- **Superheterodyne Receiver**
Superheterodyne Receiver

- The input at RF is down converted to an intermediate frequency (IF).
- Advantages: Excellent sensitivity, much lower conversion loss in detection.
- IF amplifier is more effective and stable than RF amplifier.
- IF signal simplified filtering (narrow filter) improve selectivity.
- LO OSC can be changed to track the TX frequency → IF and filtering.
- Duplexer: switches the common antenna between TX and RX (TR switch).
- Input of RX to output of processor can vary from 100 to 200dB
- STC (sensitivity time control): gain as a function of time (range)
- AGC (automatic gain control): may not used due to unavailability of low-noise amplifiers and excellent of RF mixers
- Noncoherent:
  - Low IF: lower cost
  - High IF: Wideband

Performance Considerations

- Noise Characteristics
- Noise Figure
- Radar Receiver Noise Figure
- Dynamic Range
  - Bandwidth
- IF selection and Filtering
Considerations on Noise

- Usually the first characteristics specified for a radar receiver
- The understanding of the receiver noise as the ultimate limitation on radar range performance is important.
- The ability to detect received radar echoes is ultimately limited by thermal noise, even if receiver adds no additional noise

- The lowest-noise receiver may need great a sacrifice in system performance and cost
- It is seldom a dominant factor because the noise contribution has been reduced sufficiently.

\[ T_o = 290^\circ K \] : standard noise temp.
\[ B \] : Bandwidth

\[ F = \frac{S_i/N_i}{S_o/N_o} = \frac{1}{G N_i}, \quad S_o/S_i = G \]

Noise Figure = \[ NF = 10 \log(F) \] (dB)

Output noise \[ N_o = GFN_i = GF(kT_iB) \]

Total equivalent input noise = \[ FN_i \]

Total equivalent input noise generated by receiver = \[ (F-1)N_i \]

Effective noise temp = \[ T_{eff} = (F-1)T_i \]

\[ F_i = \frac{F_i}{1 + \frac{1}{G_i}} \]

where \( G \) = front end and RF losses
\( S_i \) = conversion loss of mixer

Figure 7-3. Factors affecting the overall receiver noise figure.

Thermal Noise Characteristics

- The average thermal noise input to the receiver can be determined as \( N = kTB \), where \( k = 1.38 \times 10^{-23} \text{ (k/W)} \).
- Noise Temperature of input impedance \( T_o \).
- We generally defined Noise Factor

\[ F = \frac{S_i/N_i}{S_o/N_o} = \frac{1}{G N_i}, \quad S_o/S_i = G \]

\[ Noise \ Figure = NF = 10 \log(F) \text{ (dB)} \]

Output noise \( N_o = GFN_i = GF(kT_iB) \)

Total equivalent input noise = \( FN_i \)

Total equivalent input noise generated by receiver = \( (F-1)N_i \)

Effective noise temp = \( T_{eff} = (F-1)T_i \)
Noise of a Cascaded System

\[
S_i \rightarrow G_1 F_1 \rightarrow G_1 N_1 \rightarrow G_2 F_2 \rightarrow G_2 N_2 \rightarrow \cdots \rightarrow G_N F_N \rightarrow S_o
\]

Total input noise = \[
1 F_1 - \left( \frac{(F_1 - 1)kTB}{G_1} + \frac{(F_2 - 1)kTB}{G_1 G_2} + \cdots + \frac{(F_N - 1)kTB}{G_1 G_2 \cdots G_N} \right)kTB
\]

Total output noise = \[
(G_1 G_2 \cdots G_N) F(kTB)
\]

Cascaded Noise Figure

\[
T_E = (F_1 - 1)kTB
\]

\[
F_T = F_1 + \frac{(F_2 - 1)}{G_1} + \cdots + \frac{(F_N - 1)}{G_1 G_2 \cdots G_{N-1}}
\]

• The noise factor for a system consisting of N cascaded network can be found to be

• The effective noise for a system consisting of N cascaded network can be found to be

\[
T_E = T_E + \frac{T_{E2}}{G_1} + \cdots + \frac{T_{EN}}{G_1 G_2 \cdots G_{N-1}} = (F_2 - 1)T
\]

If the first-stage network has adequate gain he noise figure of the total network is primarily determined by the first stage.
**Chapter 7: Radar Receiver**

**An Example (RF receiver)**

![RF System Diagram](image)

- **RF Amplifier**
  - Gain: \( G_{RF} = 30 \text{dB} = 1000 \)
  - Noise Figure: \( F_{RF} = 2.3 \text{dB} = 1.698 \)

- **Mixer**
  - Gain: \( G_{M} = 23 \text{dB} = 199.5 \)
  - Noise Figure: \( F_{M} = 7.5 \text{dB} = 5.62 \)

- **IF Amplifier**
  - Gain: \( G_{IF} = 30 \text{dB} = 1000 \)
  - Noise Figure: \( F_{IF} = 1.2 \text{dB} = 1.31 \)

**Sensitivity & Max. detection Distance**

\[
F_T = F_1 + \frac{(F_2 - 1)}{G_1} + \ldots + \frac{(F_N - 1)}{G_1G_2G_{N-1}} = 1.698 + \frac{(5.62 - 1)}{1000} + \frac{(1.31 - 1)}{199.6 \times 1000} = 1.698 + 0.00462 + 1.59 \times 10^{-6} = 1.703 \text{dB}
\]

**Noise Equivalent Bandwidth**

\[
kT_0B_{1\text{MHz}} = -114 \text{dBm}
\]

**Equation:**

\[
R_{max} = \left[ \frac{P_GA_e}{4\pi^2S_{i,\text{min}}} \right]^{1/4} = \left[ \frac{100 \times 1000 \times 0.0716 \times 4}{(4\pi)^2 \times 2.5 \times 10^{-12}} \right]^{1/4} = 16416 \text{m} = 164.16 \text{km}
\]

**Maximize the receiver SNR → Matched filter**

\[
t = 10G
\]

Bandwidth is too wide, such that the sensitivity is too high. Then, the maximum range is limited.

**Example: Calculations**

\[
S_i = F \times S_o \Rightarrow S_o = \frac{S_i}{N_i} \Rightarrow N_i = \frac{S_o}{N_o} N_{i,\text{equ}}
\]

\[
S_{i,\text{min}} = F_T kT B \times (S_o/N_o)_{\text{min}} = [-114 + 10 \log(B_{\text{MHz}})] + F_T \text{dB} + (S_o/N_o)_{\text{min, dB}} = -114 + 10 \log(200) + 5 = -86 \text{dBm}
\]

\[
P_T = 80 \text{dBm} = 100 \text{kW}
\]

**RX Design**

\[
G = 30 \text{dB}
\]

\[
\sigma = 4 \text{m}^2
\]

For reliable detection, \( S_{i,\text{min}} = -66 \sim -76 \text{ (dB)} \)

\[
(S_o/N_o)_{\text{min, dB}} = 10 \sim 20 \text{ dB}
\]
Chapter 7: Radar Receiver

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Radar Receiver Noise Figure

- **DSBNF** (double sideband noise figure)
  - radio astronomy noise figure
  - radiometer noise figure
  - Radiometer-type receiver: echo occupies upper and lower sidebands
  - \[ F_{DSB} = \frac{N_0}{GkT_0(2B)} \]

- **SSBNF** (single sideband noise figure)
  - Radar: echo occupies only noise at the signal frequency
  - \[ F_{SSB} = \frac{N_0}{GkT_0(B)} = F_{DSB} \times 2 = F_{DSB,\,dB} + 3\,dB \]
  - NF (vendors) +3dB for radar NF

Dynamic Range

- The radar receiver is required to receive and detect signal levels near the receiver noise level, also be able to tolerate echo signals from large RCS targets at close range

**Receiver Dynamic Range**

- Nonlinearity
- Minimum signal level = noise
- Maximum signal level = no distortion to input power
- 1-dB compression point
- SFDR (Spurious Free Dynamic Range)
  - 1-dB SFDR: 70~100dB
- Generally, determined by mixer. Various stages following mixer do not saturate prior to mixer
- Linearity from receiver noise level to a power of about -10dB
- Without RF gain control, the useful dynamic range of a receiver is generally determined by mixer dynamic range.
Dynamic Range Improvement

- Various following the mixer (IF amplifier, detector, video amplifier) do not saturate prior to the mixer in order to preserve dynamic range

Power Control increasing dynamic range without degrading long-range detection performance

- AGC (Auto gain control): prior to the mixer will increase the effective dynamic range.
  - May fluctuate due to variations in the target cross section
  - Result in additional loss prior to the mixer. Noise level ↑, sensitivity and DR ↓.

- STC (Sensitivity Time control): may be better to vary gain as a function of time to provide more amplification for targets that are farther away far in a pulsed radar system
  - Receiver sensitivity is reduced in detecting small targets at close-in range, since gain is small at close-in range.
  - may be helpful in reducing the effects of close-range target without degrading the long-range detection performance

Dynamic Range

\[ D_3 > D_2 > D_1 \]

\[ G = R \]

\[ G = 40 \log R \]

- DR is particularly important for processing multiple echoes. Large signals may cause saturation in the receiver → masking of more distant echoes
- Provided the radar utilizes a pulse that is sufficiently short so as to discriminate at various ranges between \( R_1 \) and \( R_2 \). Gain can be variable to keep received power \( P_T \approx \text{Constant} \).

IF Selection and Filtering

Bandwidth of signal

- The basic rule of the thumb for a pulse radar application is that receiver bandwidth \( B \approx \frac{1}{\tau} \).
  - \( B \uparrow \), noise \( \uparrow \). \( 100 \text{ns pulse, } B = 10 \text{MHz} \)
  - Pulse has spectral characteristic \( B(f) \), the matched filter should have spectral characteristic \( H^*(f) \).

IF selection

- Mixer/LO implementation:
  - IF \( \downarrow \), Mixer-and-LO induced noise \( \uparrow \).
  - IF \( \uparrow \), noise from IF amplifier \( \uparrow \), since frequency \( \uparrow \), noise \( \uparrow \).
  - IF 30M~4G are common in radar application
- Availability of IF processing components.
  - IF signal-processing components (Log IFs, pulse compression, surface acoustic wave devices SAW, limiters) are available at lower frequency (30~500M)
  - The gain and filtering in the receiver usually distributed over stages of varying gains and losses.
  - Gain must be distributed so that IF stages do not saturate prior to saturation at the RF converter (RF mixer)
  - Narrowband filtering is most easily and

Transmitted waveform characteristics

- At the higher millimeter wave frequency (140G), a higher IF is required. A minimum separation of LO and TX frequencies if 750M to 1000M Hz is required.
  - Broadband systems also require higher IF frequency to minimize spurious response.
UP-Down Converter (Example)

Three-stage up-down converter

- Flitter out Image, Local leakage, IM ...

\[ f_{LO1} - f_{IF2} = 7. \]
\[ B = 400 \]

\[ f_{IF2} = f_{LO1} - f_{IF1} \]

\[ f_{LO1} - f_{IF2} = 7. \]

\[ f_{IF2} = f_{LO1} - f_{IF1} \]

Receiver Components

- Mixer
  - Single-ended,
  - Balanced

- Amplifier
  - RF
  - IF

- Diode
- Limiter
- Accumulator
- Duplexer
- Oscillator
- Isolator
- Switch
- Phase shifter
- Filter
Receiver Protection

**Duplexer**
- A single antenna for both transmission and reception.
- Responsible for protecting the receiver during transmission and for switching the antenna between TX and RX.

**Types**
- High power radius employs power-sensitive gas discharge tubes to direct the TX or RX energy
  - Transmit-receive (TR)
  - Anti-transmit-receive (ATR) tubes
- Ferrite duplexer (circulator)
  - Do not employ gas tubes
  - Use circulator, use ferrite materials
  - 25~30dB isolation

**Diode limiters**
- Designed to perform the same function as the receiver protector TR discussed above
- Reflect or absorb essentially all incident RF power above a certain level
- Ferrite or semiconductor → more reliable than TR tubes, Low insertion loss
- Pin Diode Switches
  - Fast 5 to 25 ns switching time
  - 15-30dB isolation
  - Insertion loss 2~4dB
Receiver Protection Characteristics

Table 7-1. Receiver Protector Characteristics.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Device (Single)</th>
<th>Input Power (Peak)</th>
<th>Insertion Loss (dB)</th>
<th>Leakage or Isolation</th>
<th>Recovery Time (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHF</td>
<td>TR tube</td>
<td>2 MW</td>
<td>2.0</td>
<td>1 W peak</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>TR tube</td>
<td>10 kW</td>
<td>6.0</td>
<td>2 W peak</td>
<td>50</td>
</tr>
<tr>
<td>L-band</td>
<td>TR tube</td>
<td>50 kW</td>
<td>0.4</td>
<td>1 kW peak</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Solid state</td>
<td>1 kW</td>
<td>0.4</td>
<td>0.1 avg.</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Balanced duplexer</td>
<td>50 MW</td>
<td>0.4</td>
<td>0.35 avg.</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>Branch duplexer</td>
<td>2 MW</td>
<td>0.7</td>
<td>0.25 avg.</td>
<td>35</td>
</tr>
<tr>
<td>S-band</td>
<td>TR tubes</td>
<td>100 kW</td>
<td>0.7</td>
<td>0.3 avg.</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>TR limiter</td>
<td>100 kW</td>
<td>0.5</td>
<td>0.1 avg.</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Ferrite limiter</td>
<td>20 kW</td>
<td>1.4</td>
<td>0.1 avg.</td>
<td>20</td>
</tr>
<tr>
<td>X-band</td>
<td>TR tube</td>
<td>100 kW</td>
<td>0.7</td>
<td>0.2 avg.</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>TR limiter</td>
<td>100 kW</td>
<td>0.8</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td>Kx-band</td>
<td>TR tubes</td>
<td>10 kW</td>
<td>0.5</td>
<td>0.15 avg.</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Ferrite switch</td>
<td>0.5 W avg.</td>
<td>1.1</td>
<td>40 dB</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>TR limiter</td>
<td>100 kW</td>
<td>1.7</td>
<td>0.2 avg.</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>PIN switch</td>
<td>10 W</td>
<td>1.5</td>
<td>40 dB</td>
<td>0.1</td>
</tr>
<tr>
<td>W-band</td>
<td>Ferrite switch</td>
<td>0.5 W avg.</td>
<td>1.8</td>
<td>35 dB</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>PIN switch</td>
<td>10 W</td>
<td>1.5</td>
<td>30 dB</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Chapter 7: Radar Receiver

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Mixer

- At microwave frequency, mixer are usually obtained using point contact or schottky barrier diodes.
- In some applications, the mixer may be the first device in your receiver system.
- NF (noise figure) = 1 dB at 5G, 5 dB at 95 G
- The nonlinear mixing process produces many sum and difference frequency of the signals, LO (local oscillation) and their harmonics.
- Mixing action generally described by

\[ I = f(v) = a_0 + a_1 v + a_2 v^2 + \ldots + a_n v^n \]

- Given that

\[ v(t) = V_{RF} \sin(w_{RF}t) + V_{LO} \sin(w_{LO}t) \]

the primary mixing products, \( w_{LO} \pm w_{RF} \), come from the second-order term and proportional to \( a_2 \) in amplitude.

Figure 7.6: Mixer spurious chart. (By permission, from Microwave series, ref. 12; © 1977 John Wiley & Sons, Inc.)
Mixing

\[ v^2(t) = \left[ V_{RF} \sin(w_{RF}t) + V_{LO} \sin(w_{LO}t) \right]^2 = V_{RF}^2 \sin^2 w_{RF}t + V_{LO}^2 \sin^2 w_{LO}t + 2V_{RF}V_{LO}\sin(w_{RF}t)\sin(w_{LO}t) \]

\[ V_{RF}V_{LO}[\cos(w_{RF} - w_{LO})t - \cos(w_{RF} + w_{LO})t] \]

- When the signal is mixed with the LO frequency of \( f_{RF} \) and \( f_{LO} \), and \( f_{RF} + f_{LO} \) results
- Similarly, when the image signal is mixed with the LO frequency \( f_{RF} - 2f_{IF} - f_{LO} = -f_{IF} \) and \( f_{RF} - 2f_{IF} + f_{LO} \) may results
- But recall that because of the many other powers that are generated, many harmonics and intermodulation products (IMPs). e.g.
  \[ \cos^2 x = 1/2(1 + \cos 2x) \]
  \[ \cos^3 x = 1/4(\cos 3x + 3 \cos x) \]

Non-linearity: Harmonics, Spurious

Mixer Dynamic Range

In many applications dynamic range is limited by mixer dynamic range (DR)

**Three definitions for DR**

- Low end: Thermal noise + NF_{mix}, High end: saturated output ~Lo power conversion Loss
- Low end: Thermal noise + NF_{mix}, High end: 1 dB compression point (input power at which conversion loss increases by 1 dB)
- Low end: Thermal noise + NF_{mix}, High end: input power level at which two third-order IMP just equal mixer output noise level.

Conversion (Insertion) loss for IF (5 ~ 10 dB)

**RF/LO Isolation** (12 ~ 23 dB)

**LO/IF Isolation** (10 ~ 20 dB)

**5-13 dBm** Harmonics down IMP down
**Mixer Configurations**

### Single-ended mixer
- The simplest form
- LO energy can be radiated by the receiver antenna (RF/LO isolation)
- All harmonics and IMPs will be suppressed by filtering, if required.

### Balanced mixer
- reduce spurious response, cancellation of DC components at the IF output, and convenient separation of LO and RF inputs.
- The even harmonics of one of the input signals are suppressed. Harmonics of the LO signal are suppressed.

---

**Image-reject mixer**

![Image-reject mixer diagram](image)

**Table 7.3. Mixer Comparison Guide**

<table>
<thead>
<tr>
<th>Mixer Type</th>
<th>Balanced (dB)</th>
<th>LO Spurious</th>
<th>LO/RF Isolation</th>
<th>LO/IF Isolation</th>
<th>Image-reject</th>
<th>Image-Recency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-ended</td>
<td>Good</td>
<td>Medium</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Balanced</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

---

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Detector

Superheterodyne receiver

- At least two stages of down conversion in the detection process
- The first down conversion is accomplished by the first detector (Mixer)
- Information at IF consists of the phase, amplitude, and frequency of received echo signal.

Second-stage detection

- Square Law detection: No LO signal, output voltage is proportional to input RF power (square of RF input voltage)
  - Tangential signal sensitivity (TSS):
- Synchronous detection: With an LO input, the detection process is linear
  - second LO (COHO) is at the same freq. as the IF.
  - I/Q provides amp. and phase information.
- Phase detection: IF signals are hard-limited (const. amp.), only phase information.

Amplifier

- 1dB compression point (Output) ~ 30dBm
- 3rd order 2-tone intercept point (Output) ~ 35 dB
- NF ~ 7.5dB
- BW ~ 150 MHz
- Gain ~ 16 dB
- $P_{\text{noise}} = -114 + 10 \log (\text{BW}) + \text{NF} = -114 + 10\log(150)+7.5 = -84.5$ dBm

1dB compression Dynamic Range

- $P_1 (\text{input}) = 30 - 16 = 14$
- $\text{DR}_{1\text{dB}} = P_1 (\text{input}) - P_{\text{noise}} = 14 - (-84.5) = 98$ dB

Spurious Free Dynamic Range (SFDR)

- $P_1 = 35 - 16 = 19$ dBm (input)
- SFDR = $2/3(P_1 - P_{\text{noise}}) = 2/3 (19+84.5) = 69$ dB

Logarithmic IF amplifier/detector (log amp)

- Output video is proportional to the logarithm of the RF input.
- Extremely wide dynamic range (70 ~ 80 dB)
- No AGC to achieve the wide dynamic range.
Coherent Radar Receiver Design

**Fully Coherent Detection**

- RF transmitted signal → the combination of a STALO (stable LO) and a COHO (coherent LO) IF oscillator
- The sum is formed in an up-converter and amplified using a pulsed RF amplifier.
- On receive, IF signal (60MHz ~ 4 GHz) is the same frequency as the COHO,
- IF signal is amplified, filtered..., and then down-converted to baseband Doppler by mixing with COHO.
- Orthogonal mixer → I and Q signal components
- Signal-processing circuitry consist of MTI or pulse-Doppler filtering.

**Coherent on Receive**

- maximum coherence or MTI improvement is not required.
- A noncoherent transmitter can be employed

---

**Coherent Receiver on Receive**

**Tuned COHO**

- receive phase tracks transmitter phase → stability can be maintained in COHO during the time bet. transmission and reception, and repeatability of phase locking of COHO from pulse to pulse.

**Tuned COHO**

- highly stable COHO to tune transmitter to match it in frequency → stability can be realized.
- correct each target echo before applying the signal to moving target filter

---

Figure 7.23. Fully coherent receiver.

Figure 7.24. Examples of coherent-on-receive implementations.
Pulse Compression

- Allow a radar to use a long pulse to achieve high radiated energy and simultaneously to obtain range resolution
- Use freq. or phase modulation to widen the signal bandwidth
- Linear FM pulse compression
- A stable but noncoherent LO
- RF and IF processing circuitry must be broadband
- IF amplifier must have sufficient bandwidth and linear phase over the band
- Compressive filters used are surface acoustic wave (SAW) devices. analog device is used to obtained a compressed video output.

Frequency Stepped Coherent Receiver

**High-range resolution**

- Wideband frequency stepped waveform
- processing the received echo using FFT
- Coherent or noncoherent detection
- Coherent processing can increase the receiver SNR
- STALO with a frequency synthesizer whose output frequency is selectable in \( N \) discrete steps of \( \Delta f \) step size
- Total bandwidth = \( N \times \Delta f \)
- Wide bandwidth requirement for the receiver front end (circulator, protector, RF mixer
- effectively generates a wideband signal while maintaining a narrowband receiver.

**Range Resolution**

\[
\text{Range Resolution} = \frac{c}{2B_T} \quad B_x = N \times \Delta f
\]

\[
c = 3 \times 10^{10} \text{(cm/s)}
\]

**Ex: 128 10MHz steps and a 100-ns pulse width**

\[
R_{\text{res}} = \frac{3 \times 10^{10} \text{(cm/s)}}{2 \times 128 \times 10^7} = 11.72\text{cm}
\]

\[
(S/N)_{\text{impr}} = 10 \log \left(\frac{1280 \times 10^6}{10^7}\right) = 21\text{dB}
\]

**Figure 7-26.** Transmitted stepped frequency packet. The time between pulses is the radar interpulse period (PRF)^{-1}. 

**Figure 7-25.** Example of an FM pulse compression receiver.

**Figure 15-1.** Pulse compression processing in a radar system.