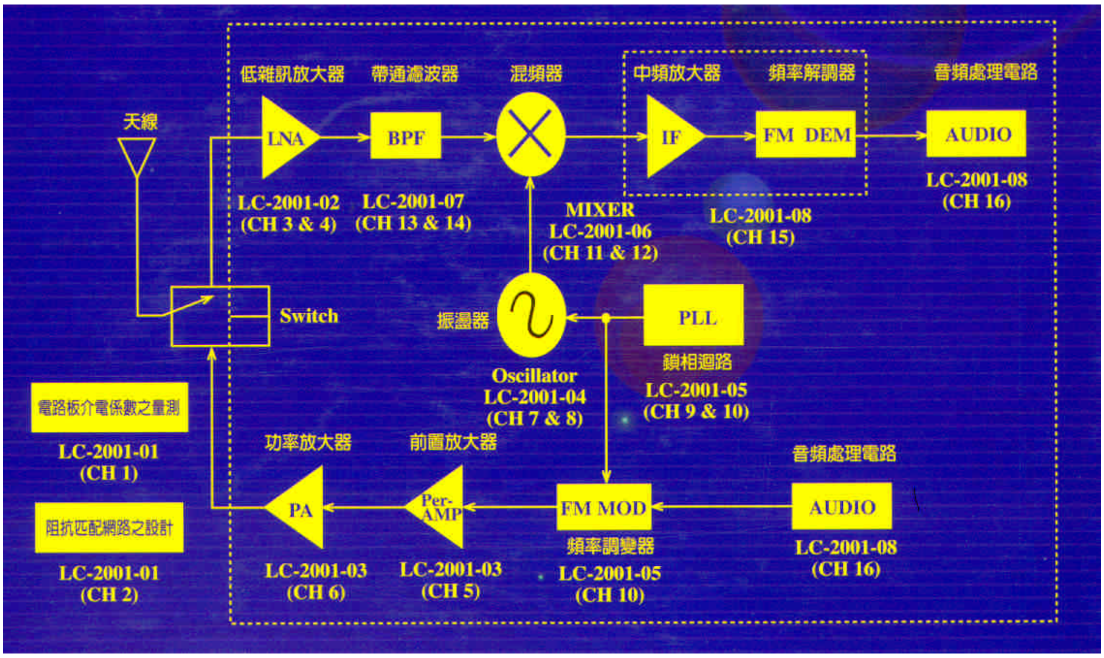
Chapter 7
Radar Receiver



Radar System Design

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

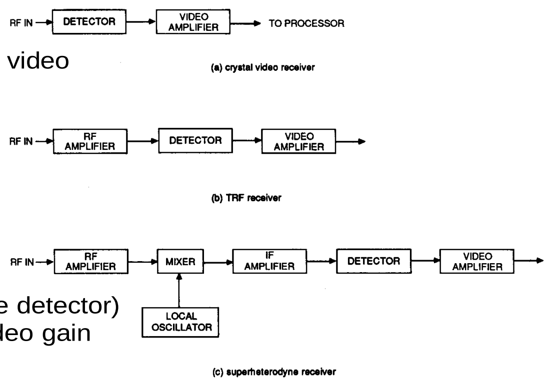
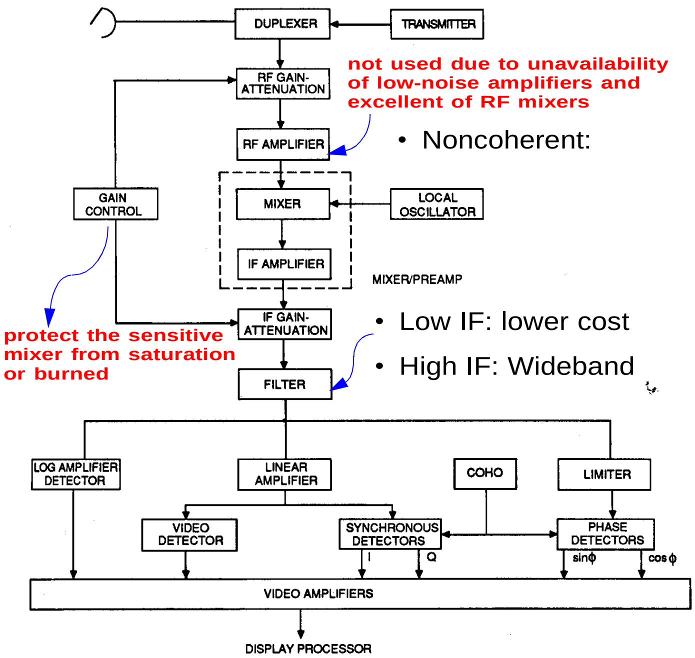


Figure 7-1. Simple block diagram of (a) a crystal video receiver, (b) a TRF receiver, and (c) a superheterodyne receiver.

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

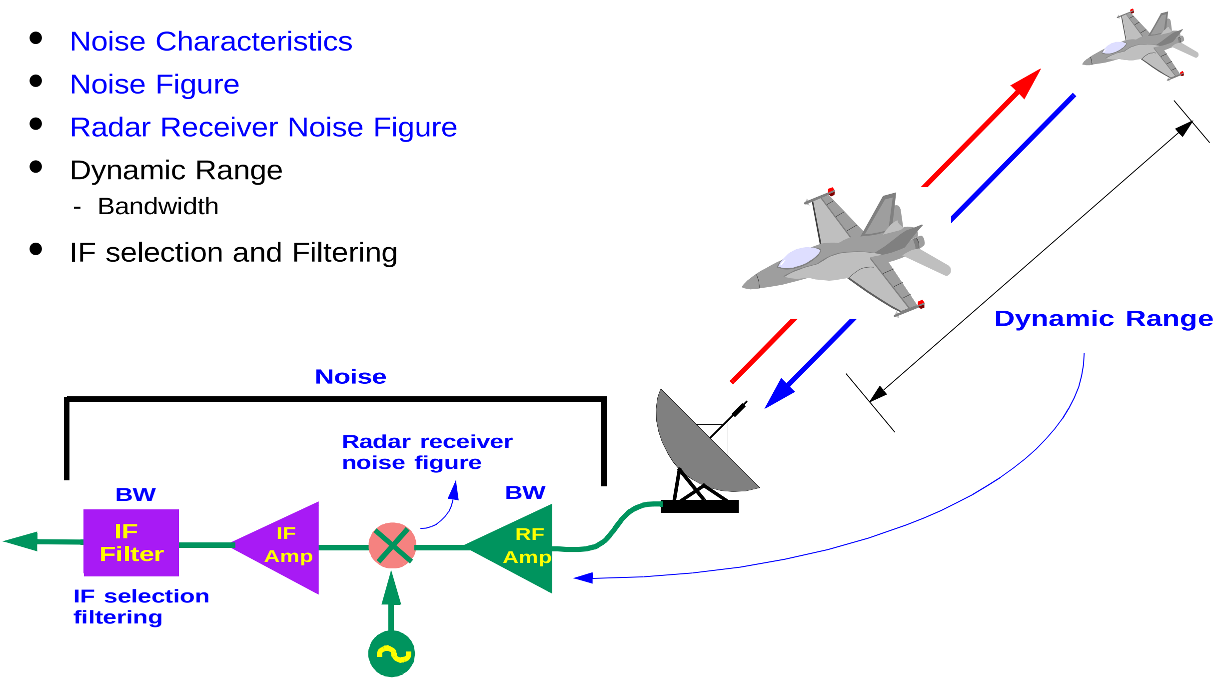


- Noncoherent:
- Low IF: lower cost
- High IF: Wideband

Figure 7-2. General block diagram of a superheterodyne receiver.

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.

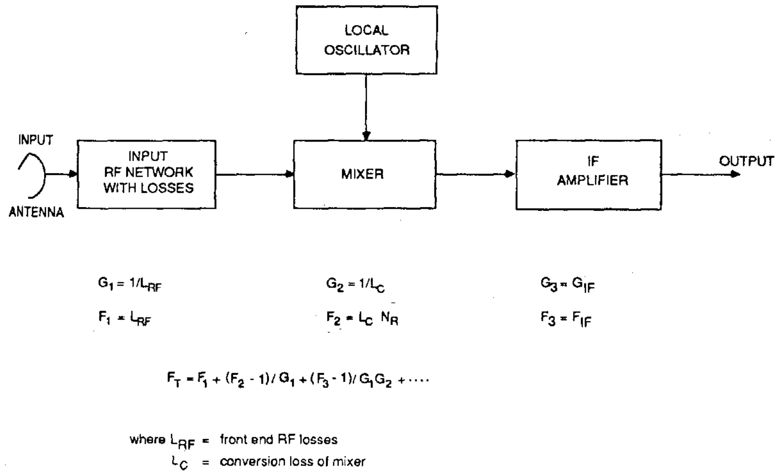
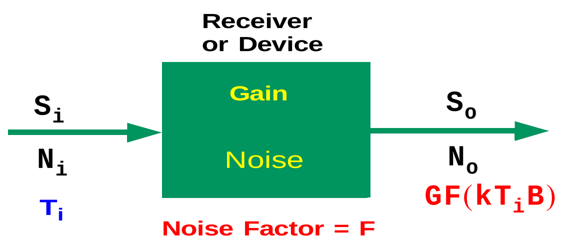
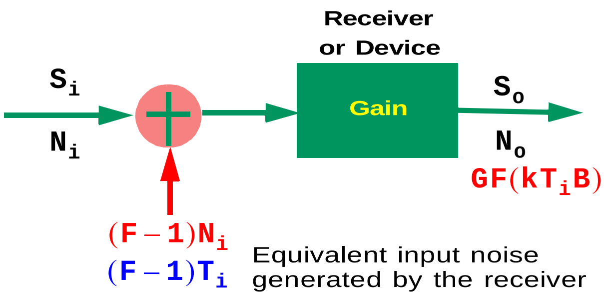


Figure 7-3. Factors affecting the overall receiver noise figure.

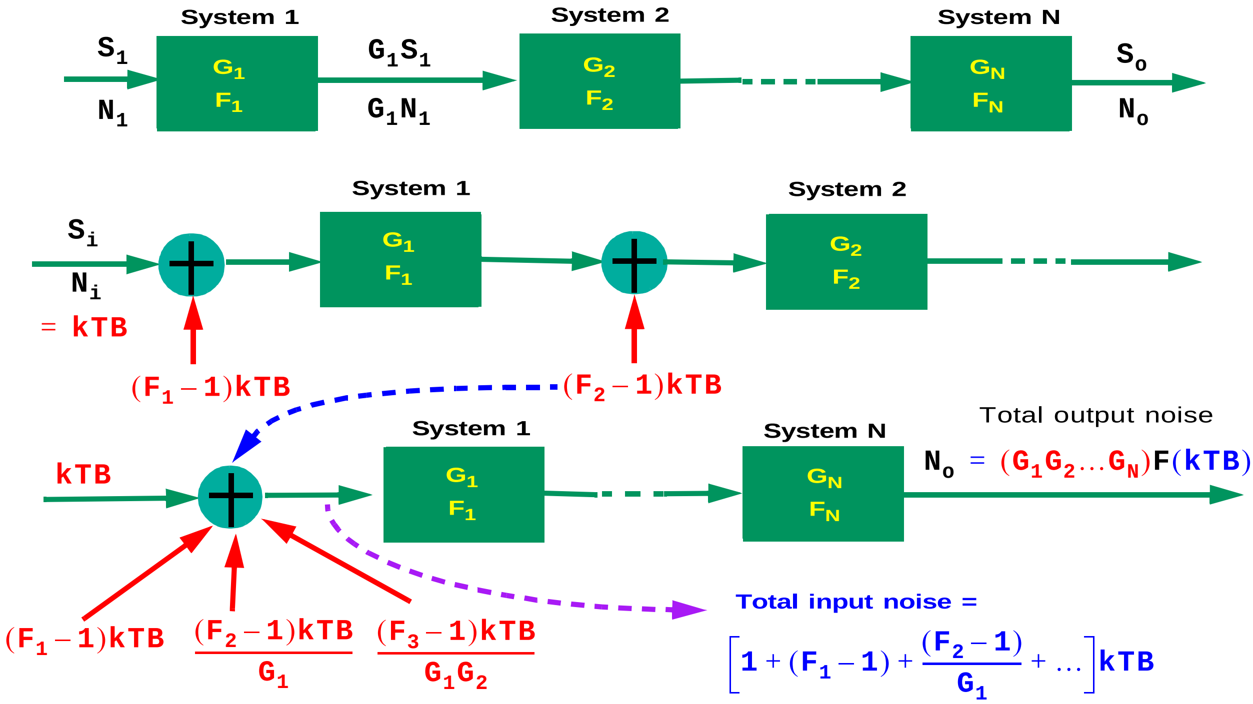
Thermal Noise Characteristics

- The average thermal noise input to the receiver can be determined as $N = kTB$, where $k = 1.38 \times 10^{-23}$ (k/w).
  T = Noise Temperature of input impedance $T_o = 290°k$: standard noise temp. B : Bandwidth
- We generally defined Noise Factor
  $$F = \frac{S_i/N_i}{S_o/N_o} = \frac{1}{G}\frac{N_o}{N_i}, \quad S_o/S_i = G$$
- Noise Figure = $NF = 10\mathrm{Log}(F)(\mathrm{dB})$
- 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 = $T_{eff} = (F-1)T_i$

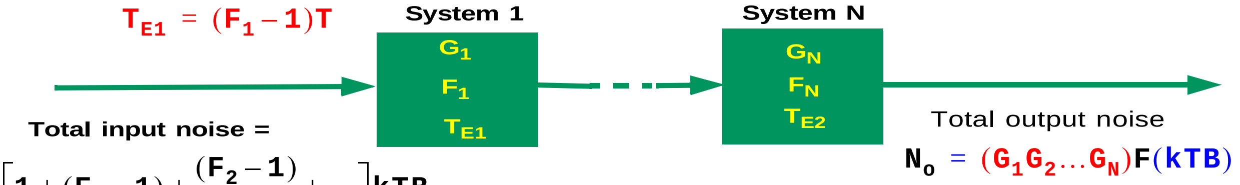




Noise of a Cascaded



Cascaded Noise Figure



Total input noise =

$$\left[1+(F_1-1)+\frac{(F_2-1)}{G_1}+\ldots\right]kTB$$

Receiver Temp

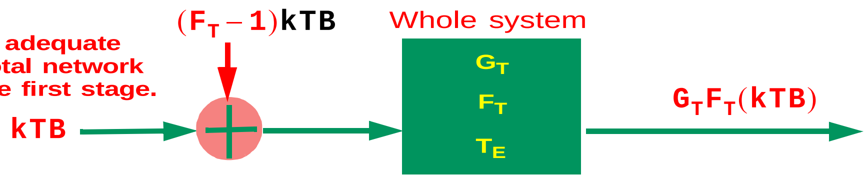
$$= \left[F_1+\frac{(F_2-1)}{G_1}+\ldots+\frac{(F_N-1)}{G_1G_2\ldots G_{N-1}}\right]kTB = k\left(T+T_{E1}+\frac{T_{E2}}{G_1}+\ldots+\frac{T_{EN}}{G_1G_2\ldots G_{N-1}}\right)B = k(T+T_E)B$$

- 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

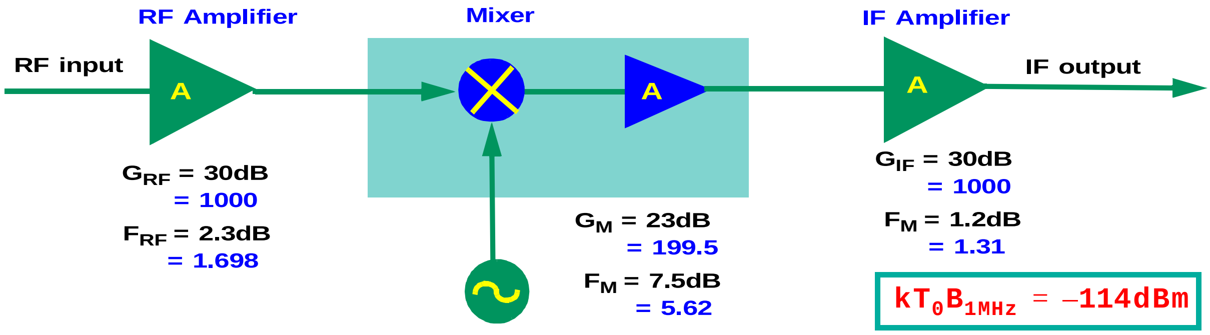
$$F_T = F_1+\frac{(F_2-1)}{G_1}+\ldots+\frac{(F_{N-1}-1)}{G_1G_2\ldots G_{N-1}}$$

$$T_E = T_{E1}+\frac{T_{E2}}{G_1}+\ldots+\frac{T_{EN}}{G_1G_2\ldots G_{N-1}} = (F_T-1)T$$

If the first-stage network has adequate gain he noise figure of the total network is primarily determined by the first stage.



An Example (RF receiver)



$$F_T = F_1 + \frac{(F_2-1)}{G_1} + \ldots + \frac{(F_N-1)}{G_1G_2G_{N-1}} = 1.698 + \frac{(5.62-1)}{1000} + \frac{(1.31-1)}{199.6\times 1000}$$

$$= 1.698 + 0.00462 + 1.59\times 10^{-6} = 1.703 = 2.31\text{dB}$$

$$T_E = (F_T-1)T = (1.703-1)290°\text{k} = 203.87°\text{k} \quad \text{, if BW = 1MHz}$$

$$N_{i,equ} = F_T kTB = 1.703\times(1.38\times10^{-23})\times 290\times(1\times10^6) = -111.65\text{dBm}$$

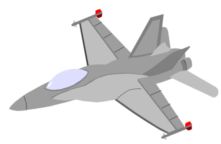
$$N_o = N_{i,equ}G = -111.65 + (30+23+30) = -28.8\text{dBm}$$

Sensitivity & Max. detection Distance)

$$R_{max} = \left[\frac{P_tGA_e\sigma}{(4\pi)^2S_{i,min}}\right]^{1/4} = \left[\frac{100000\times1000\times0.0716\times4}{(4\pi)^2\times2.5\times10^{-12}}\right]^{1/4}$$

$$= 16416\text{m} = 164.16\text{km}$$

$$A_e = \frac{\lambda^2 G}{4\pi} = \frac{(3\times10^{-2})^2 1000}{4\pi} = 0.0716$$



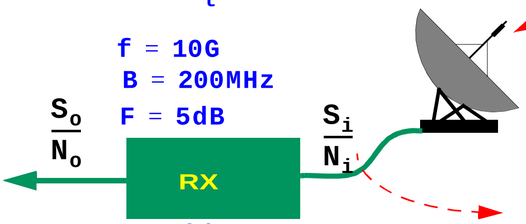
$\sigma = 4\text{m}^2$

R_{max}

$G = 30\text{dB}$

$P_t = 80\text{dBm} = 100\text{kW}$

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



$(S_o/N_o)_{min} = 0\text{dB}$

$(S_o/N_o)_{min,dB} = 10\sim20\text{dB}$ for reliable detection

$\Rightarrow S_{i,min} = -66\sim-76(\text{dB})$

Maximize the receiver SNR → Matched filte $B\sim1/\tau$

$$\frac{S_i}{N_i} = F\times\frac{S_o}{N_o} \Rightarrow \frac{S_o}{N_o} = \frac{S_i}{N_{i,equ}} \Rightarrow S_i = (FN_i)\times\frac{S_o}{N_o}$$

FN_i

$$S_{i,min} = F_T kTB\times(S_o/N_o)_{min}$$

$$= [-114 + 10\log(B_{MHz})] + F_{T,dB} + (S_o/N_o)_{min,dB}$$

$$= -114 + 10\log(200) + 5 + 0 = -86\text{dBm}$$

$$= 2.5\times10^{-9}\text{mW}$$

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
  - $F_{DSB} = \frac{1}{GkT_o(2B)} N_o$
- SSBNF(single sideband noise figure)
  - Radar: echo occupies only noise at the signal frequency
  - $F_{SSB} = \frac{1}{GkT_o(B)} N_o = F_{DSB} \times 2 = F_{DSB,\,dB} + 3dB$
  - NF (venders) +3dB for radar NF

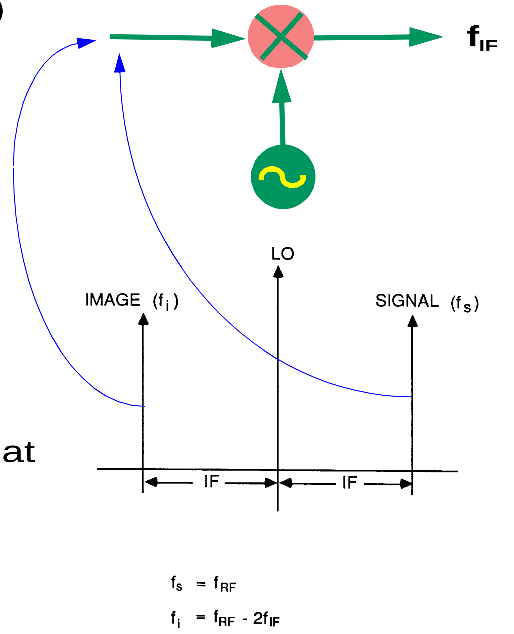


Figure 7-4. Mixer response to both the signal frequency and an image frequency.

Dynamic Range

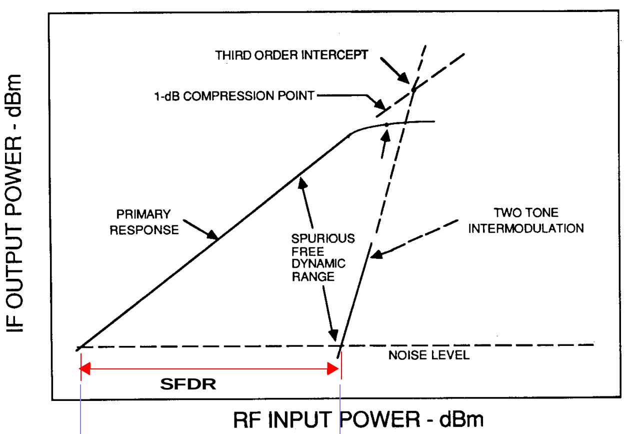
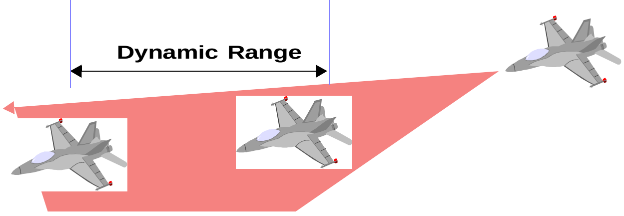


Figure 7-10. Mixer input-output relationship.



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

Receiver Dynamic Range

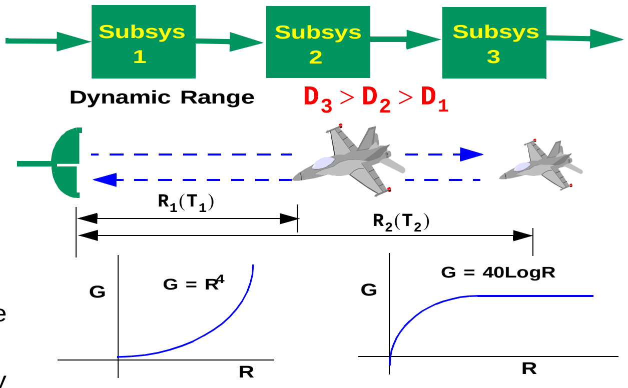
- Nonlinearity
- Minimum signal level = noise
- Maximum signal level = no distortion to input power
- 1-dB compression point
- SFDR (Spurious Free Dynamic Range)
- 1-dB SFDR: 70~100dB
- Generally, is determined by mixer. Various stages following mixer do not saturate prior to mixer
- linearity from receiver 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



- 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 $P_r \approx Constant$.

IF Selection and Filtering

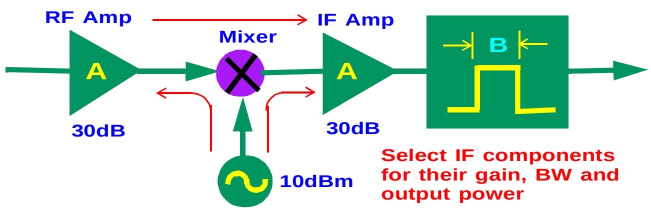
Bandwidth of signal

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

IF selection

- Mixer/LO implementation:
  - IF ↓, Mixer-and- LO induced noise ↑ .
  - IF ↑, noise from IF amplifier ↑, since frequency ↑, noise ↑ .
  - 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

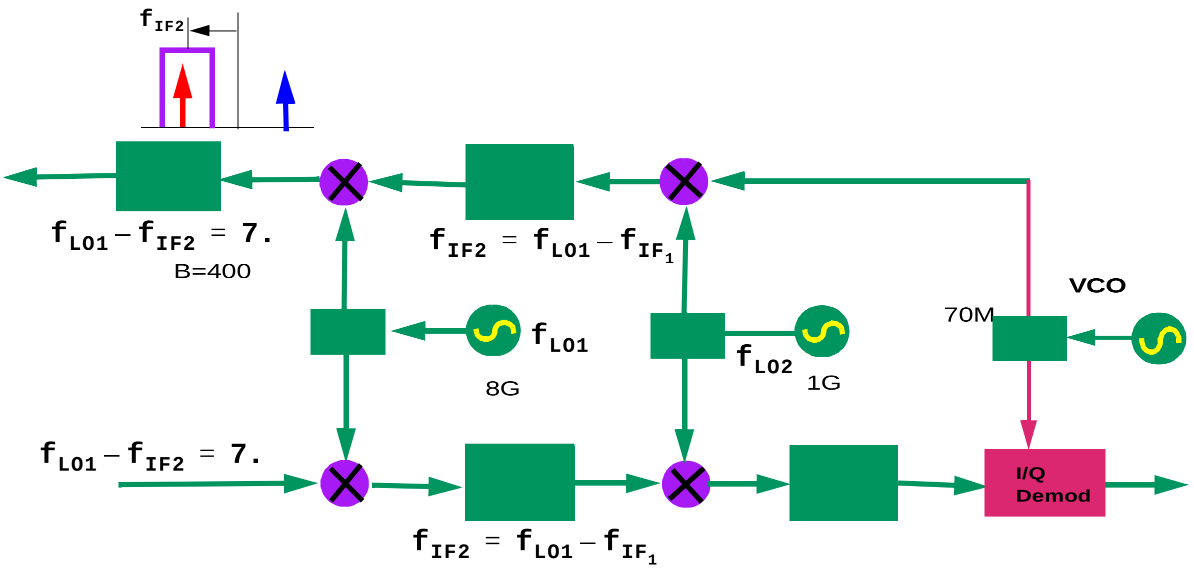


- Transmitted waveform characteristics
  - At the higher millimeter wave frequency (140G), a higher IF is required. A minimum separation of LO and TX frequencies if 750M to 1000M Hz is required.
  - Broadband systems also require higher IF frequency to minimize spurious response.

UP-Down Converter (Example)

Three-stage up-down converter

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



Radar System Design

Receiver Components

Mixer

- Single-ended,
- Balanced

Amplifier

- RF
- IF

Diode

Limiter

Accumulator

Duplexer

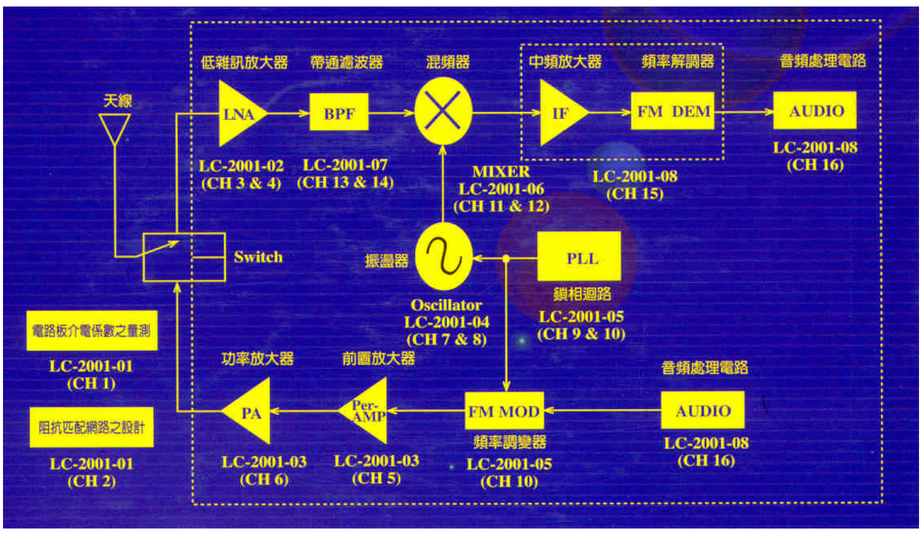
Oscillator

Isolator

Switch

Phase shiftier

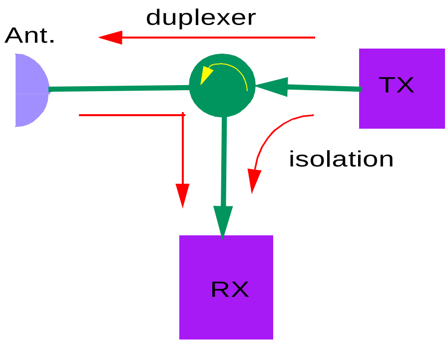
Filter



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

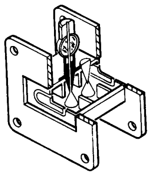


Figure 7-5. Cross-sectional view of a gas TR tube.

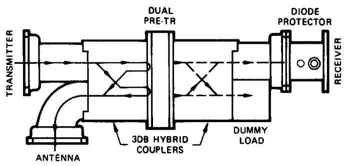


Figure 7-6. Balanced duplexer with dual TR (shown in transmit). (From ref. 7)

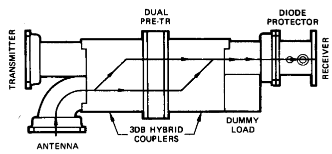


Figure 7-7. Balanced duplexer with dual ATR and diode protector (shown in receive). (From ref. 7)

Radar System Design

Receiver Protection

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

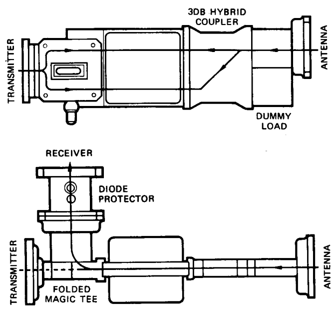
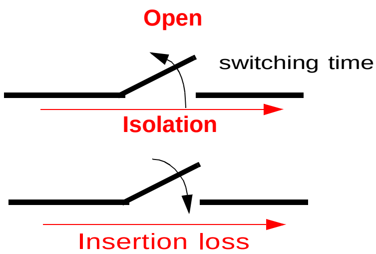
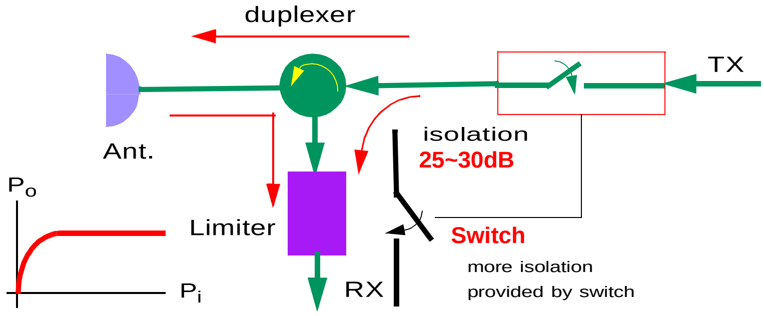


Figure 7-8. Example of a ferrite duplexer (shown in receive). (From ref. 7)





Receiver Protection Characteristics

Table 7-1. Receiver Protector Characteristics.

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

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.

F_o: output Freq. F_2: LO Freq. F_1: input Freq.

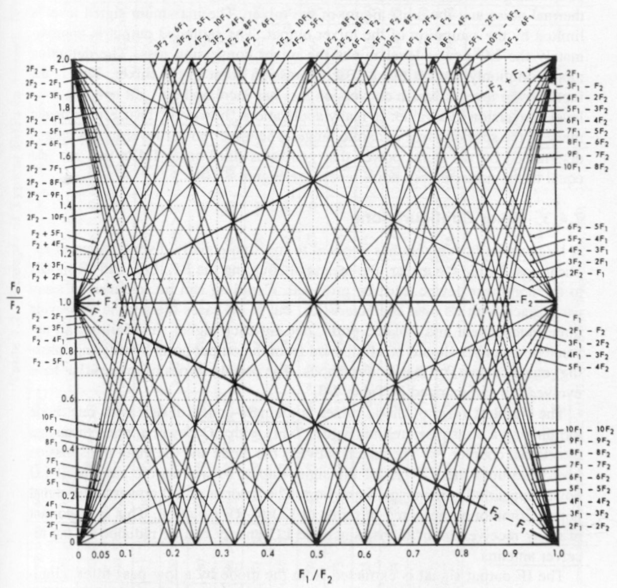


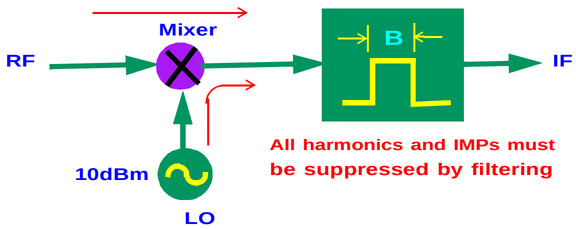
Figure 7-9. Mixer spurious chart. (By permission, from Manessewitsch, ref. 12; © 1976 John Wiley & Sons, Inc.)

Mixing

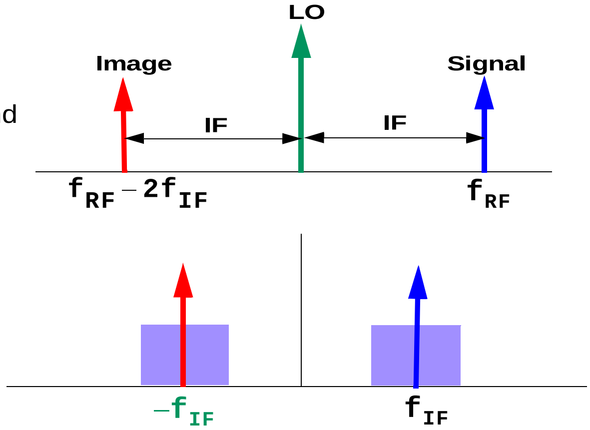
$$v^2(t) = [V_{RF}\sin(w_{RF}t) + V_{LO}\sin(w_{LO}t)]^2$$

$$= V_{RF}^2\sin^2 w_{RF}t + V_{LO}^2\sin^2 w_{LO}t + 2V_{RF}V_{LO}\sin(w_{RF}t)\sin(w_{LO}t)$$

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



- When the signal is mixed with the LO frequency of $f_{RF} - f_{LO} = f_{IF}$ 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

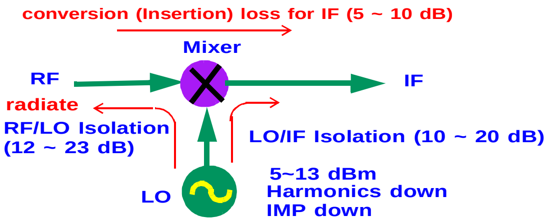


Mixer Dynamic Range

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.**



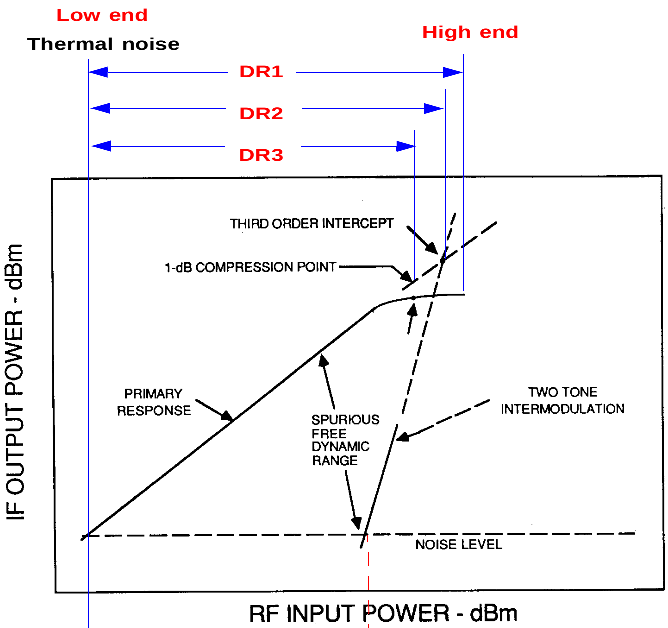


Figure 7-10. Mixer input–output relationship.

Mixer Configurations

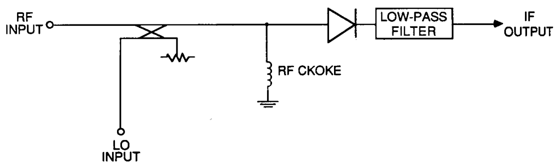


Figure 7-11. Schematic representation of a single-ended mixer.

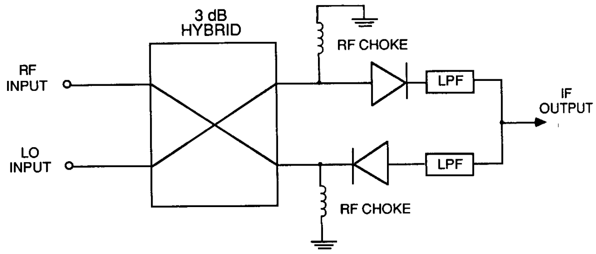


Figure 7-12. Schematic representation of a balanced mixer.

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.

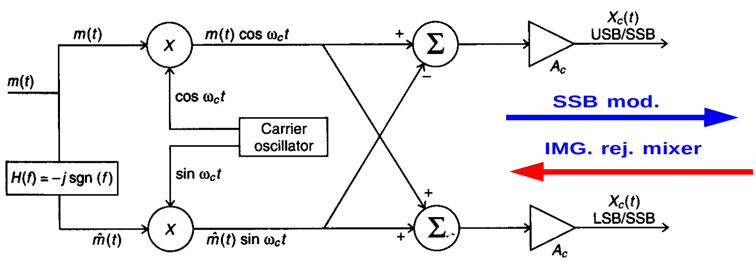
Balanced mixer

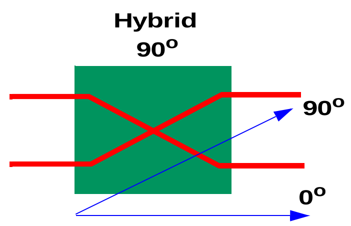
- reduce spurious response, cancellation of DC components at the IF output, and convenient separation of LO and RF inputs.
- The even harmonics of one of the input signals are suppressed. Harmonics of the LO signal are suppressed.

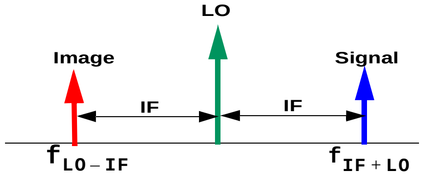
Table 7-3. Mixer Comparison Guide

Performance Parameter	Mixer Type: Single-ended	Balanced (90°)	Balanced (180°)	Double-balanced	Image-reject	Image-Recovery
Conversion Loss	Good 8–10 dB	Good 8–10 dB	Good 8–10 dB	Very Good 6–7 dB	Good 8–10 dB	Excellent 5 dB
VSWR LO, RF	Good, Poor	Good Good	Fair Fair	Poor Poor	Good Good	Good Good
LO/RF Isolation	Fair 12–18 dB	Poor <12 dB	Very Good >23 dB	Very Good >23 dB	Good 18–23 dB	Very Good >23 dB
LO Power Required (unbiased)	+13 dBm	+5 dBm	+5 dBm	+10 dBm	+7 dBm	+7 dBm
Spurious Rejection	Poor	Fair	Fair Odd: Fair	Good	Fair	Fair
Harmonic Suppression	Poor	Fair	Even: Good	Very Good	Even: Good Odd: Fair	Even: Good Odd: Fair

Image-reject mixer







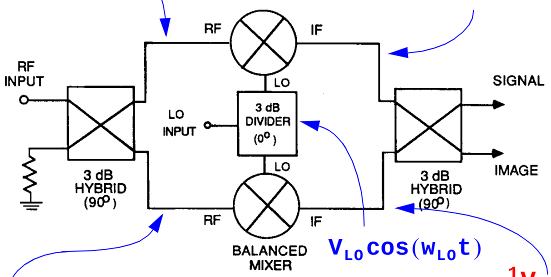
f_{LO-IF} f_{IF+LO}

$V_{RF}\cos(w_{IF}t + w_{LO}t + \phi)$

$V_{IM}\cos(-w_{IF}t + w_{LO}t + \phi)$

$\frac{1}{2}V_{RF}V_{LO}\cos(w_{IF}t + \phi)$

$\frac{1}{2}V_{IM}V_{LO}\cos(w_{IF}t - \phi)$



SIGNAL $\frac{1}{2}V_{RF}V_{LO}\cos(w_{IF}t + \phi) + \frac{1}{2}V_{RF}V_{LO}\cos(w_{IF}t + \phi - \pi) = 0$

$\frac{1}{2}V_{IM}V_{LO}\cos(w_{IF}t - \phi) + \frac{1}{2}V_{IM}V_{LO}\cos(w_{IF}t - \phi)$

IMAGE $\frac{1}{2}V_{RF}V_{LO}\sin(w_{IF}t + \phi) + \frac{1}{2}V_{RF}V_{LO}\sin(w_{IF}t + \phi)$

$\frac{1}{2}V_{IM}V_{LO}\sin(w_{IF}t - \phi) - \frac{1}{2}V_{IM}V_{LO}\sin(w_{IF}t - \phi) = 0$

$V_{LO}\cos(w_{LO}t)$

Figure 7-13. Schematic representation of an image rejection mixer.

$V_{RF}\sin(w_{IF}t + w_{LO}t + \phi)$

$V_{IM}\sin(-w_{IF}t + w_{LO}t + \phi)$

$\frac{1}{2}V_{RF}V_{LO}\sin(w_{IF}t + \phi)$

$-\frac{1}{2}V_{IM}V_{LO}\sin(w_{IF}t - \phi)$

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.

increase RF input signal until minimum peak of video signal plus noise is the same as the maximum peak of the video noise.

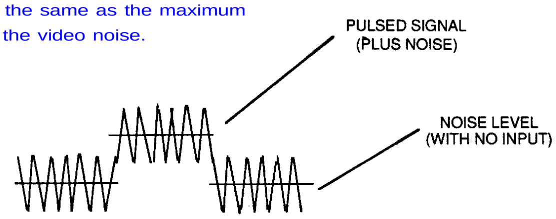


Figure 7-15. Example of an oscilloscope display in determining the TSS.

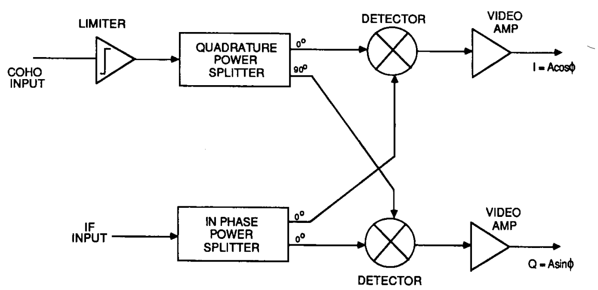


Figure 7-16. Example of in-phase (I) and quadrature (Q) synchronous detection stages.

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_{noise} = -114 + 10 log (BW)+ NF = -114 +10log(150)+7.5 = -84.5 dBm

1dB compression Dynamic Range

- $P_{1\ (input)}$ = 30 - 16 = 14
- $DR_{1dB} = P_{1\ (input)} - P_{noise}$ = 14-(-84.5) = 98dB

Spurious Free Dynamic Range (SFDR)

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

Logarithmic IF amplifier/detector (og 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.

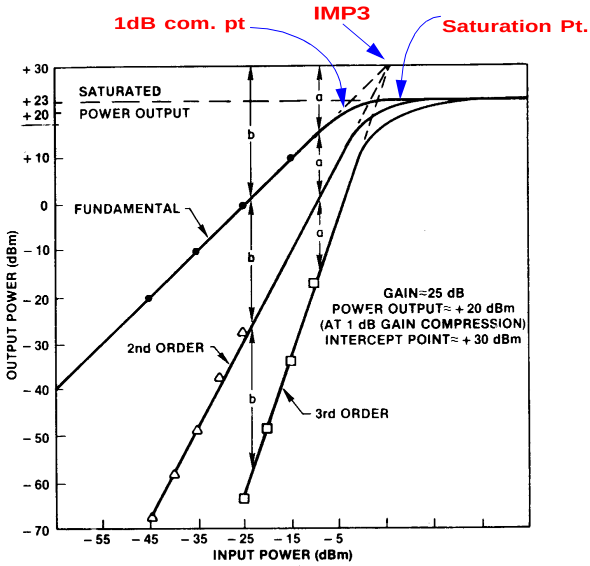
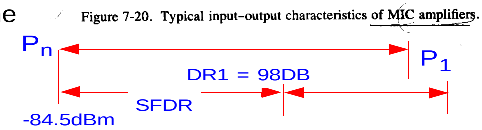


Figure 7-20. Typical input-output characteristics of MIC amplifiers. (From ref. 16)



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 noncherent transmitter can be employed

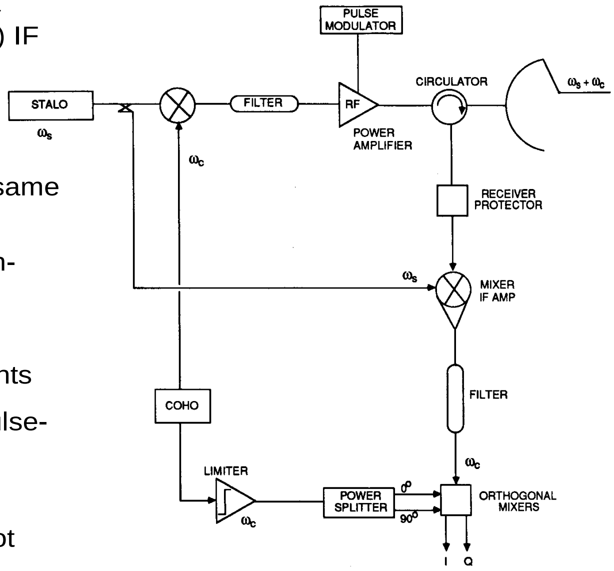


Figure 7-23. Fully coherent receiver.

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

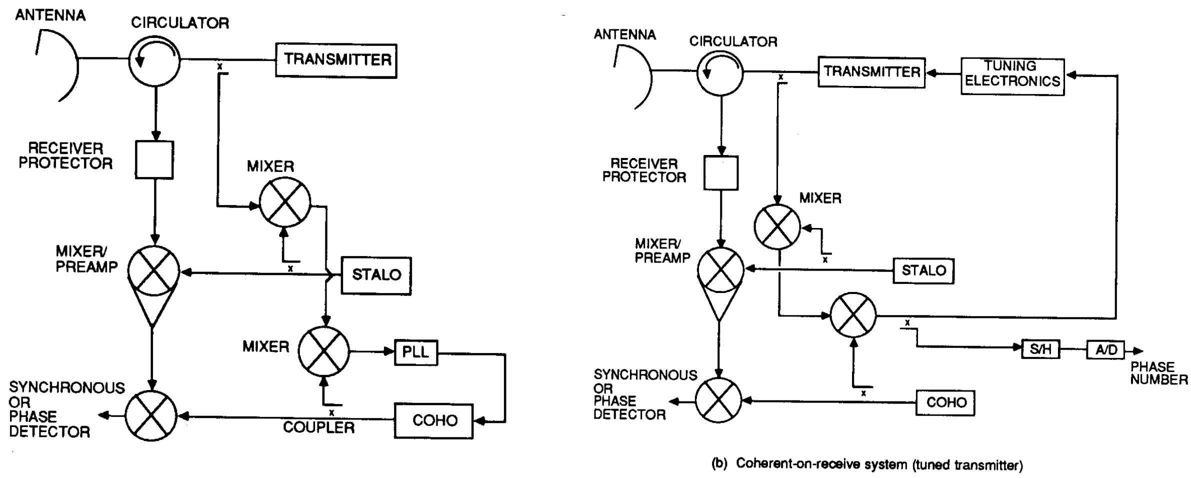


Figure 7-24. Examples of coherent-on-receive implementations.

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 wider 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.

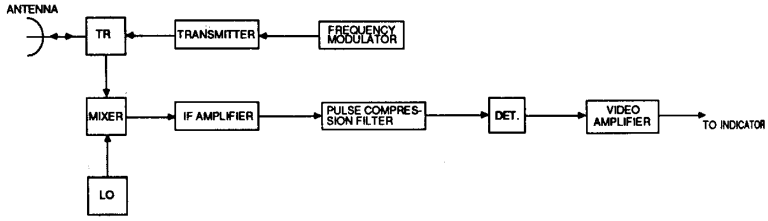


Figure 7-25. Example of an FM pulse compression receiver.

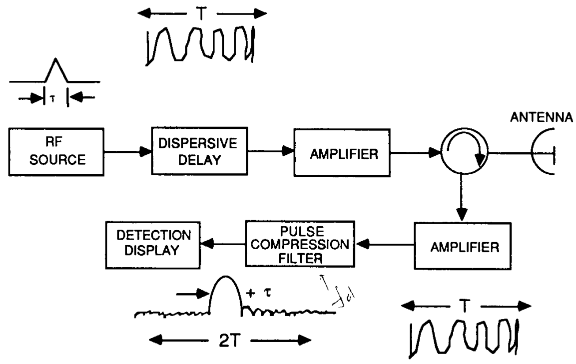


Figure 15-1. Pulse compression processing in a radar system.

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 Δf 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.

$$\text{Range Resolution} = c/2B_T \qquad B_T = N \times \Delta f$$

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

$$(S/N)_{impr} = 10 \log(B_T/B)$$

B = inverse of TX pulse wic (matched filter approx.)

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

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

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

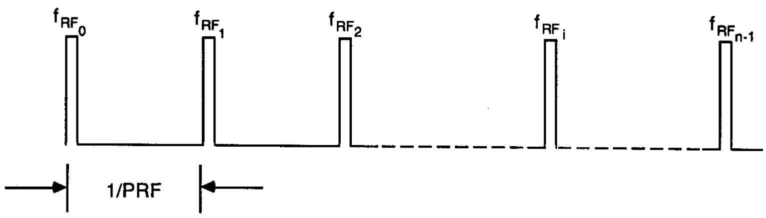


Figure 7-26. Transmitted stepped frequency packet. The time between pulses is the radar interpulse period $(PRF)^{-1}$.