EITN90 Radar and Remote Sensing
Lecture 9: Radar transmitters and receivers

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Learning outcomes of this lecture

In this lecture we will

- Learn about the basic parameters of transmitters and receivers.
- See typical transmitter and receiver configurations.
- Understand different frequency stages in the receiver chain.
- See influence of receiver and ADC dynamic range.

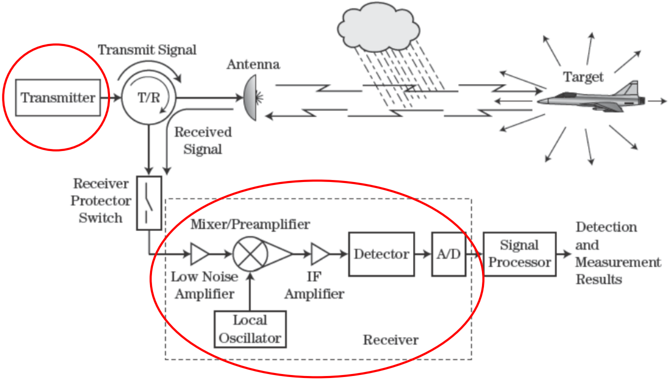


FIGURE 1-1 ■ Major elements of the radar transmission/reception process.

Outline

1. **Transmitters**
   - Transmitter configurations and parameters
   - Power sources and amplifiers
   - Modulators and power supplies
   - EM transmitter impacts and operational considerations
2. **Receivers**
   - Receiver types
   - Major receiver functions
   - Demodulation
   - Receiver noise power
   - Receiver dynamic range
   - Analog-to-digital data conversion
3. **Conclusions**

Outline

Outline

The transmitter in a pulsed radar

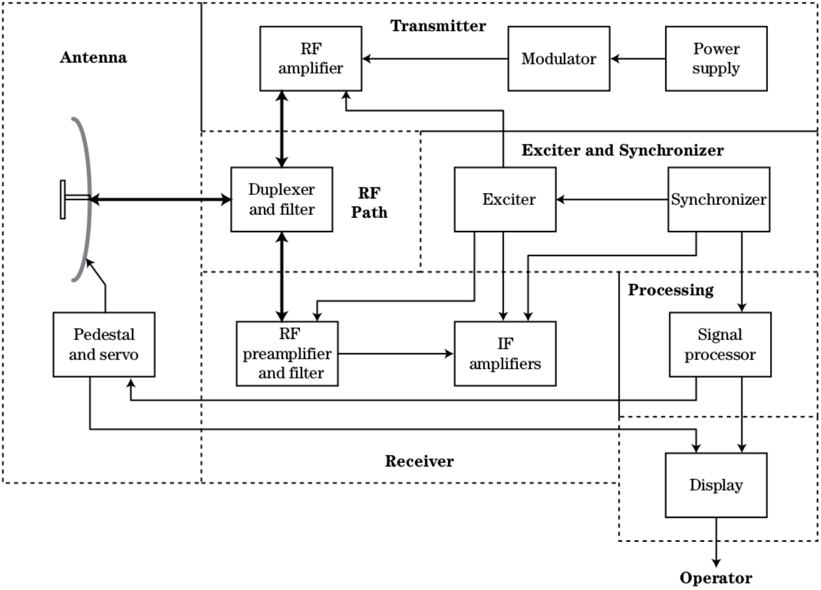


FIGURE 10-1 ■ Block diagram of typical pulsed radar. (From [1]. With permission.)

The transmitter in a phased array

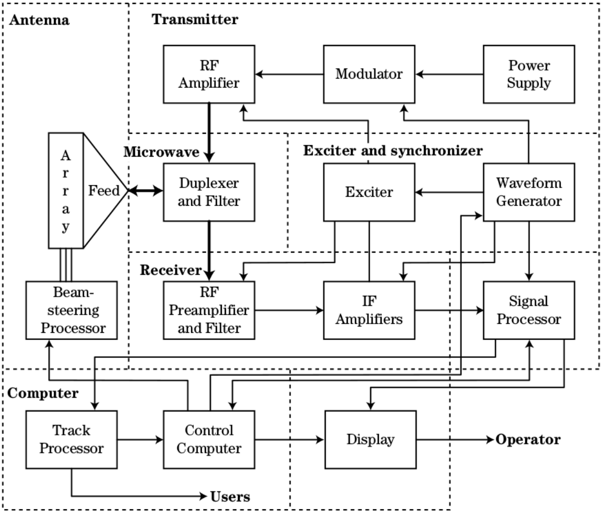


FIGURE 10-2 ■ Block diagram of a typical phased array radar. (From [1]. With permission.)

Above is a passive array. In an active array, lower-power T/R-modules are placed at each array antenna element.

Radar transmitter parameters

Average RF output power P_{ave} in terms of peak power P_{p}, pulse time τ, and pulse repetition frequency PRF:

$$P_{\mathrm{ave}} = P_{\mathrm{p}} \underbrace{\tau \cdot \mathrm{PRF}}_{=\text{duty cycle}}$$

Transmitter efficiency (typically in the order of 15% to 35%)

$$\eta_{\mathrm{t}} = \frac{P_{\mathrm{ave}}}{P_{\mathrm{DC}}}$$

Overall radar efficiency (around 5% to 25% or more)

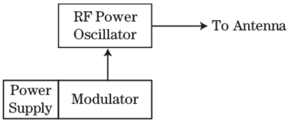
$$\eta_{\mathrm{r}} = \frac{P_{\mathrm{ave}}}{P_{\mathrm{DC}} L_{\mathrm{m}} L_{\Omega}}$$

$L_{\mathrm{m}} =$ transmitter to antenna loss factor.
$L_{\Omega} =$ antenna ohmic loss factor.

Transmitter configurations

Free running oscillator (direct use of the RF power, often noncoherent):

FIGURE 10-3 ■ Free-running oscillator-based transmitter.



Master oscillator / power amplifier (amplification of RF power, often coherent):

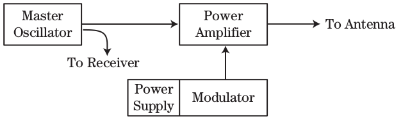
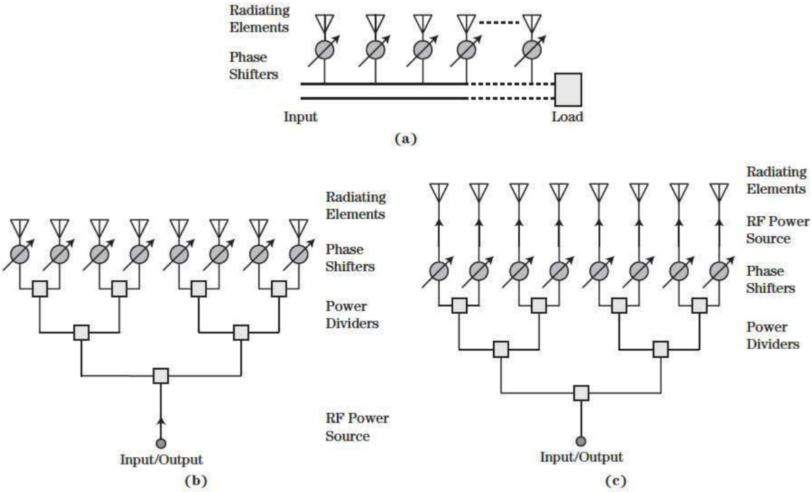


FIGURE 10-4 ■ Master oscillator/ power amplifier transmitter.

▸ Discussion

Feeding of array antenna



Distributing the feed using transmission lines.

Feeding of array antenna, continued

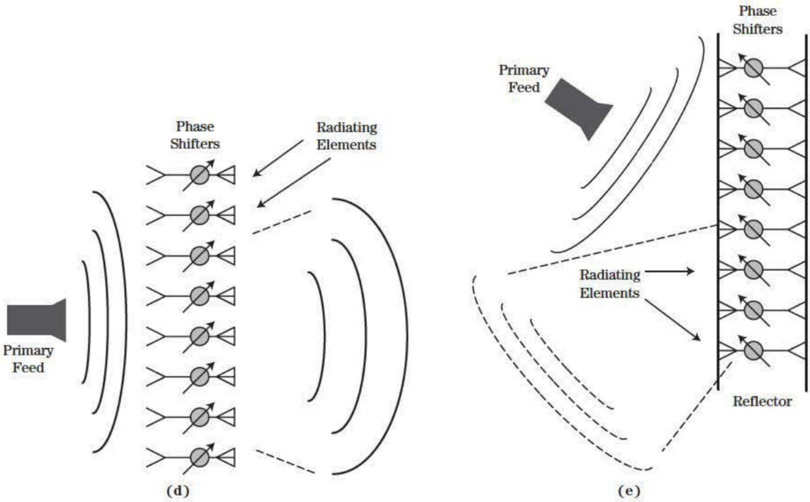


FIGURE 10-5 ■ Examples of phased array feed types. (a) Constrained series feed. (b) Constrained corporate feed. (c) Constrained distributed feed. (d) In-line space-fed array. (e) Reflect space-fed array.

Outline

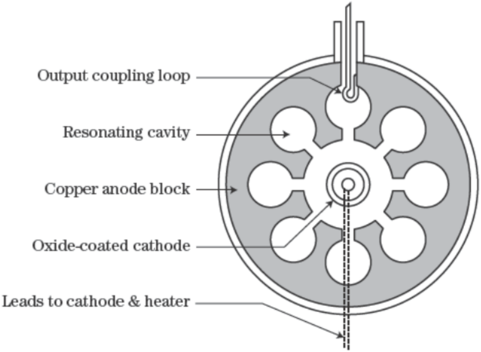
Different power sources

Two major variants of power sources can be identified, both as oscillators and amplifiers:

- Vacuum electron devices (VED, high power, relatively narrow bandwidth, bulky)
- Solid state devices (GaAs, GaN, SiC, lower power, wide bandwidth, flexible and integrable)

The magnetron

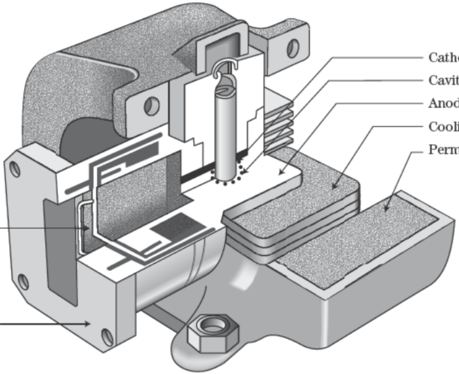
FIGURE 10-8 ■ Cross section of a magnetron tube.



Electrons are emitted from the cathode, and moves in circular orbits inside the cavity. The startup process is random, hence the pulses are incoherent. See for instance http://www.radartutorial.eu/08.transmitters/Magnetron.en.html for more in-depth explanation. You can also follow the course EITN80 Electrodynamics, starting next study period.

The magnetron, physical appearance

FIGURE 10-9 ■ Cutaway drawing of a typical magnetron.



Klystron

FIGURE 10-12 ■
Schematic view of a two-cavity klystron tube.

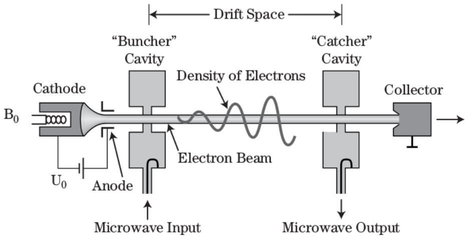


FIGURE 10-13 ■
A variety of klystron tubes. (Photo courtesy of CPI. With permission.)

http://www.radartutorial.eu/08.transmitters/Klystron.en.html

Travelling wave tube (TWT)

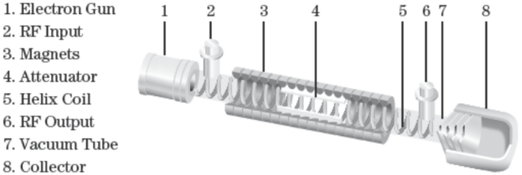


FIGURE 10-14 ■ Functional diagram of a traveling wave tube.

Careful design makes the electromagnetic wave on the helix coil to propagate at the same speed as the electron beam, coupling power from the electron beam to the RF port.

http://www.radartutorial.eu/08.transmitters/Traveling Wave Tube.en.html

Some common vacuum devices

TABLE 10-1 ■ Compilation of Characteristics of Common Vacuum Devices

Tube Type	Frequency / Bandwidth	Power Out (Typical)	Attributes / Drawbacks	Applications
Klystron	0.1–300 GHz / 5–10%	10 kW CW ** 10 MW Pulse	High Power 40–60% Efficient Low Noise / Narrow Bandwidth	Radar Television Industrial Heating Satellite Uplinks Medical Therapy Science
Traveling Wave Tube (Helix)	1–90 GHz / Wide Bandwidth 2–3 Octaves*	20 W CW 20 kW Pulse	Broad Bandwidth / Power Handling Limitations Efficiency	Electronic Warfare Communications Commercial Broadcasting Industrial Applications
Coupled-Cavity TWT	1–200 GHz / 10–20%	300 W CW 250 kW Pulse	Average Power Capability / Complex & Expensive Slow Wave Structure	Airborne Radar Satellite Communications AEGIS FC Illuminator
Magnetron	1–90 GHz / N/A	100 W CW 10 MW Pulse	Simple–Inexpensive Rugged / Noisy	Radar/Medical Industrial Heating
Crossed-Field Amplifier	1-30 GHz / 10–20%	1000 W CW 5 MW Pulse	Compact Size 30–40% Efficient / Complex and Expensive Slow Wave Structure	Transportable Radars Shipboard Radar Seeker Radar Industrial Heating
Gyrotron	30–200 GHz / 10% Max	0.2–3 MW Pulse	High Power at High Frequencies / High Voltage Required	High-Frequency Radar Fusion Accelerators Industrial Heating

*One octave is the range defined where the highest frequency is twice the lowest (e.g., 2–4, 4–8).
**DOE's APT klystrons will run at 1 MW CW.
Source: From [15] (with permission).

Solid state T/R modules

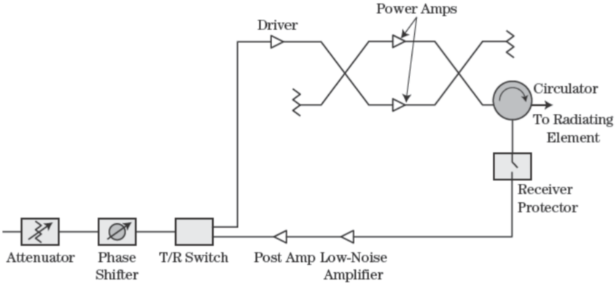
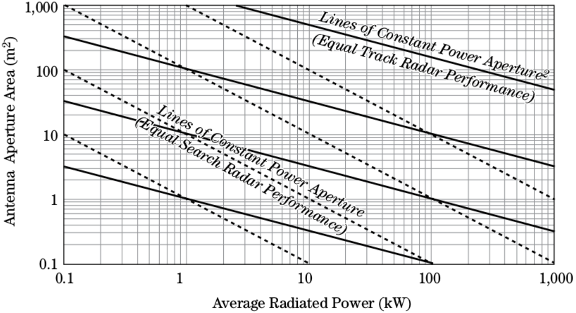


FIGURE 10-16 ■ Example T/R module architecture.

- Attenuator control of receive gain.
- Phase shifter for beam steering.
- Circulator improves match to antenna.
- Receiver is protected from high power by switch.

Trade-off power-aperture

FIGURE 10-17 ■ Aperture area and radiated power for constant PA and PA^2.



Constant $P_\mathrm{t} A_\mathrm{e}$ = search radar.
Constant $P_\mathrm{t} A_\mathrm{e}^2$ = track radar.

Solid state active-aperture arrays

Curve for fixed $P_{\mathrm{t}} A_{\mathrm{e}} G \sim P_{\mathrm{t}} A_{\mathrm{e}}^2$.

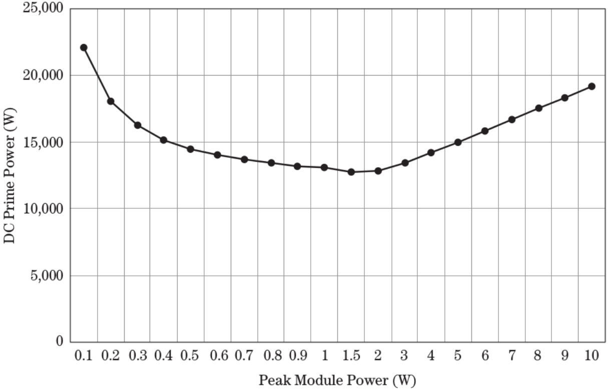


FIGURE 10-18 ■ Example phased array radar prime power requirement as a function of peak module power for a given level of power-aperture-gain product.

At low module transmit power (large aperture), receive-side is dominating DC prime power, increasing as aperture increases.
At high module transmit power, DC prime power needs to increase to sustain increased transmit power.

Outline

Pulse forming network

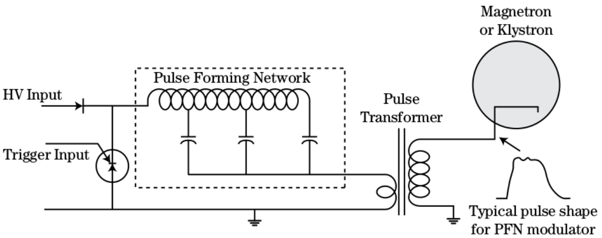


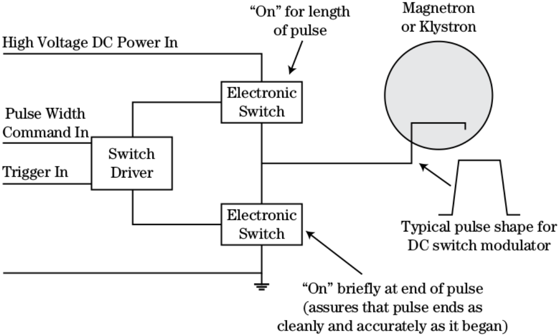
FIGURE 10-21 Simplified diagram of a PFN modulator.

The pulse forming network creates a pulse with intended pulse length, modulating an RF power source. The trailing edge of the pulse may not be well defined, since it is based on the discharge characteristics of the PFN.

Discussion

Active-switch modulator

FIGURE 10-22 ■ Simplified diagram of an active switch modulator.



To have both leading and trailing edges well defined, on- and off-switches can be employed. Solid state switches provide fast switching, but may require stacking in series to handle high voltage.

Power supplies

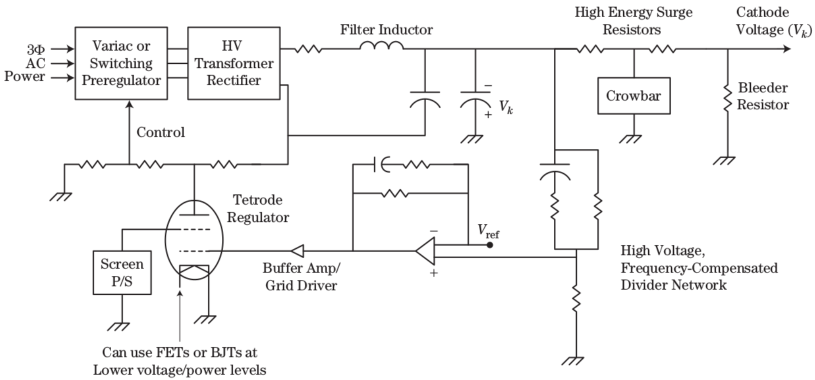


FIGURE 10-23 ■ Typical high voltage power supply for a radar transmitter.

Not all parts of this schematic are explained in the book. Do not worry too much, it is quite specialized knowledge.

Power supplies, active aperture

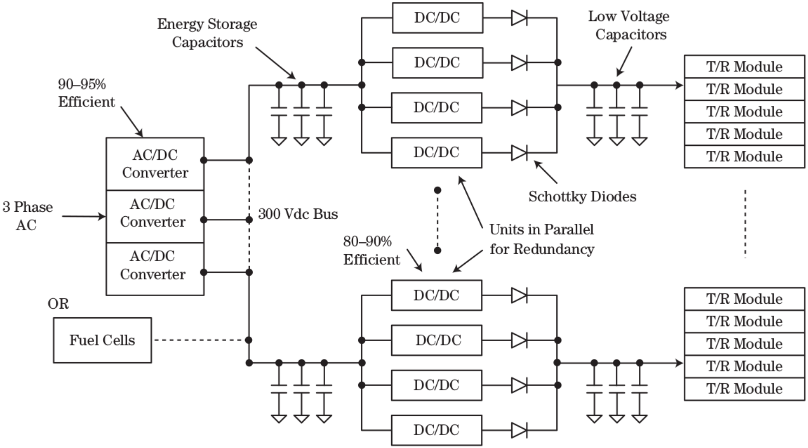


FIGURE 10-25 ■ An active aperture power supply configuration.

The parallel architecture of an active array promotes distribution of the power supply across the array as well.

Outline

Radar Spectrum Engineering Criteria (RSEC)

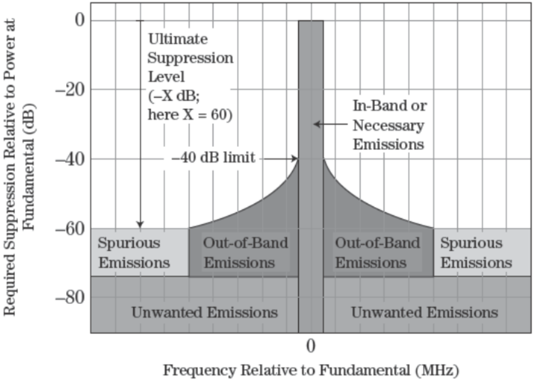


FIGURE 10-26 ■ Various signal domains considered by the RSEC.

There are regulations for the spectral emission from radars.

Radar Spectrum Engineering Criteria (RSEC)

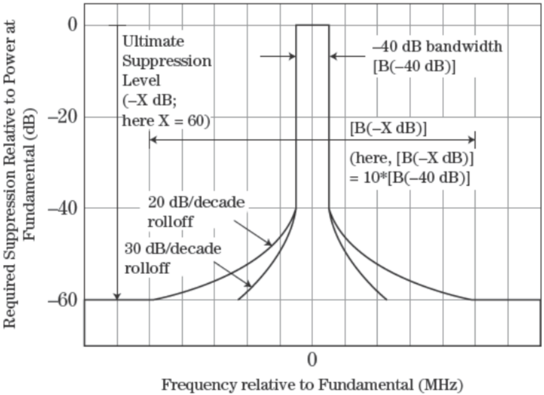
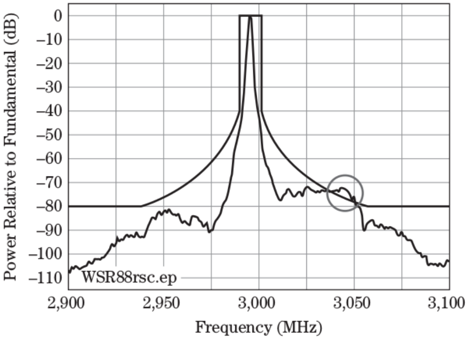


FIGURE 10-27 Generic RSEC emissions box.

There are regulations for the spectral emission from radars.

Radar Spectrum Engineering Criteria (RSEC)

FIGURE 10-28 ■ Figure shows a measured emission within the RSEC box. At about 3050 MHz the system exceeds the allowable limits for the subject group.



Breach of regulations at 3 050 MHz.

Spectral purity

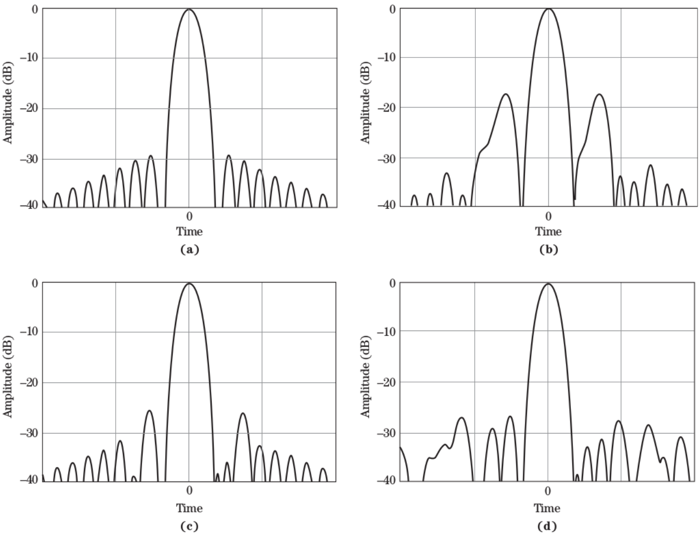


FIGURE 10-29 ■ Time sidelobe response with intrapulse modulation errors. (a) Idealized response with no intrapulse modulation error. (b) 3 cycles of 10 degrees rms sinusoidal modulation error. (c) 3 cycles of 2 degrees rms sinusoidal modulation error. (d) 10 degrees random modulation error.

Operational considerations

Reliability

- High operating temperature and voltages reduce life time.
- Increased risk for failure when concentrating to few sources.
- Temperature sensors and power control may prevent failure.
- Highly parallel systems provide high redundance.

Heat can be removed in essentially three ways:

- Normal air-convection currents (low-power devices)
- Forced-air cooling
- Liquid cooling

Safety issues

- High power: overvoltage, overcurrent.
- X-rays, material dependent wavelengths, lead shielding.
- Hazardous materials used, many are toxic.
- Strong RF field may ignite electro-explosive devices.
- Tissue heating from RF exposure.

Outline

Outline

Radar receivers

FIGURE 11-1 ■ General receiver functions.

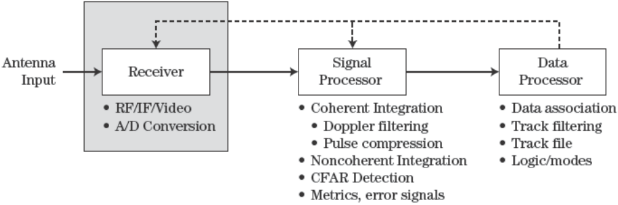
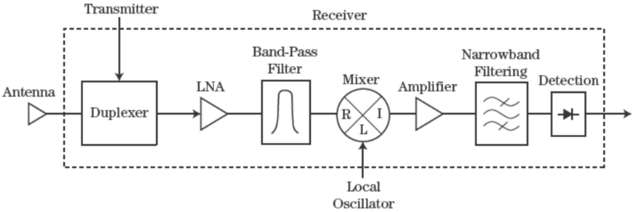


FIGURE 11-2 ■ Major receiver elements.



Receivers typically provide down-conversion of the received signal, amplification, and filtering.

▸ Discussion

Receiver types

Receiver types discussed in the book include

- Crystal video receivers (rectifier)
- Superregenerative receivers
- Homodyne receivers (mixing with transmitted signal)
- Superheterodyne receivers (mixing with LO)
- Digital receivers (digitization of received signal)
- Instantaneous frequency measurement receivers
- Channelized receivers (polarization, I/Q, monopulse etc)

Different frequencies

A number of frequencies are used in describing receivers (in decreasing amplitude):

- RF = radio frequency, carrier wave
- LO = local oscillator, reference inside radar
- IF = intermediate frequency, RF – LO
- VF = video frequency, baseband

Crystal video receivers

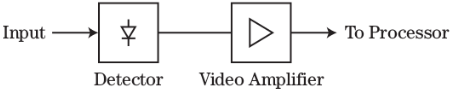


FIGURE 11-3 Crystal video receiver.

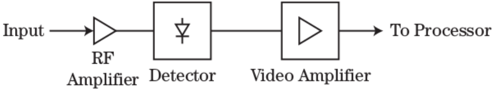
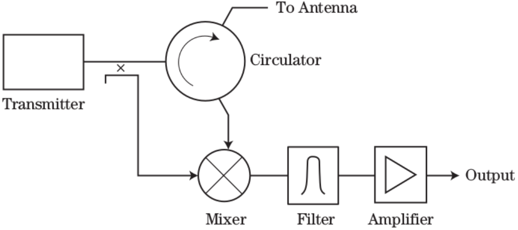


FIGURE 11-4 Modified crystal video receiver.

Detects the amplitude envelope of the radar signal, incoherent as it does not preserve phase information.

Homodyne receivers

FIGURE 11-5 ■
Homodyne receiver.



Uses the transmitted signal as reference, requires the transmitter to be on while receiving.

Superheterodyne receivers

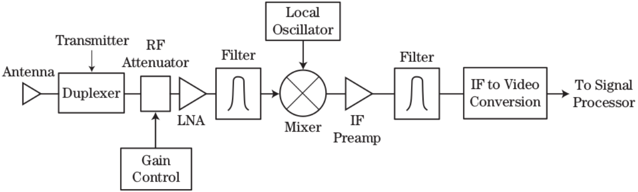


FIGURE 11-6 ■ Generic superheterodyne receiver configuration.

The LO can often be tuned to follow the RF. The gain control of the attenuator can be used to reduce sensitivity to near targets, and improve dynamic range. Bandpass filters remove unwanted mixer products and out-of-band signals.

Outline

RF preselection

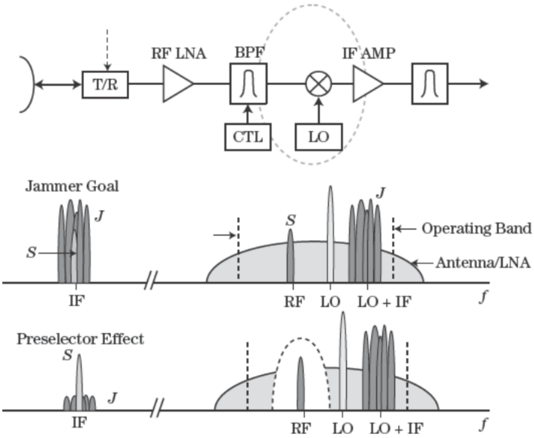


FIGURE 11-7 ■ Effects of preselection on rejection of jammer signals.

Filtering the RF can reduce sensitivity to jammers. No effect if the jammer is exactly at the RF.

Mixer products

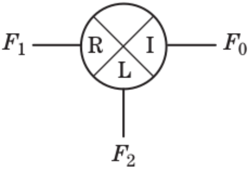


FIGURE 11-10 ■

Mixer model.

The output of the mixer can be described as

$$I_0 = F(V) = a_0 + a_1 V + a_2 V^2 + a_3 V^3 + \cdots + a_n V^n + \cdots$$

With two different frequencies, $V = V_1 \sin(2\pi f_1 t) + V_2 \sin(2\pi f_2 t)$, the output will have frequencies at all combinations

$$m f_1 + n f_2, \quad m, n = 0, \pm 1, \pm 2, \ldots$$

Typically, $f_1 - f_2$ is desired, and $f_1 + f_2$ (and others) need to be rejected.

Multiple downconversions

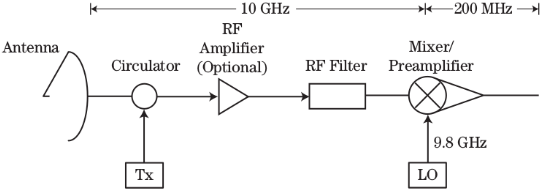


FIGURE 11-8 ■ Single downconversion process.

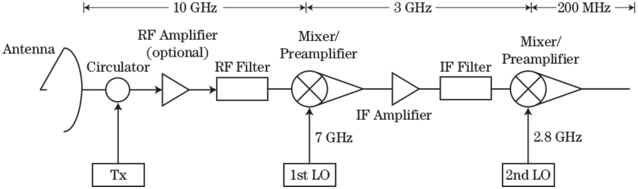


FIGURE 11-9 ■ Double downconversion process.

Several frequency stages can help the design of filters. The extra stages make it easier to design the filters, since intermodulation products are far apart. Example: $2 \cdot 7 - 10 = 4$, $2 \cdot (10 - 7) = 6$.

Outline

Diode and square-law detectors

FIGURE 11-11 ■
Basic diode detector.

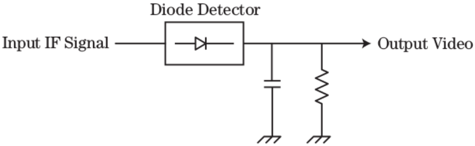
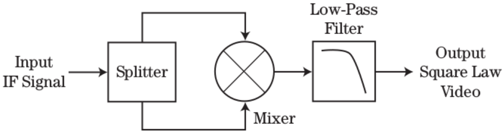


FIGURE 11-12 ■
Square law detector.



The RF signal can be converted to video based on amplitude or square amplitude. Affects the probability distributions used in detection theory.

Log amplifier

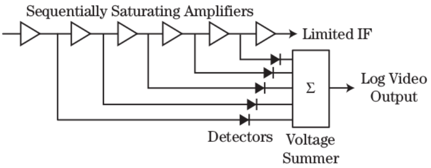


FIGURE 11-13 Log amplifier block diagram.

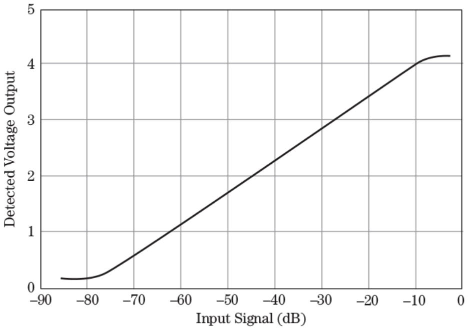


FIGURE 11-14 Typical log amplifier output characteristic.

Provides a linear response over large dynamic range in dB scale.

Coherent demodulation (I/Q)

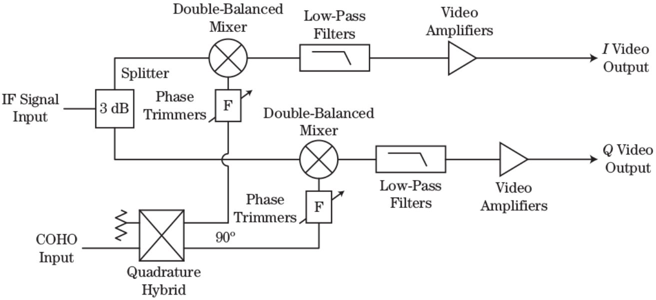


FIGURE 11-16 Circuit for analog coherent I and Q processing.

Mixing with two signals, one in-phase (I) and one in quadrature (Q), makes it possible to keep phase information in the downconverted signal. The analytic signal is

$$a = I + \mathrm{j}Q = A\mathrm{e}^{\mathrm{j}\phi}$$

with amplitude $A = \sqrt{I^2 + Q^2}$ and phase $\phi = \arg(I + \mathrm{j}Q)$.

Outline

Signal to noise ratio and noise figure

The signal to noise ratio is given by the radar range equation (note there is a λ^2 factor missing in the book's equation (11.9))

$$\mathrm{SNR} = \frac{P_\mathrm{t} G^2 \lambda^2 \sigma}{(4\pi)^3 k T_0 B_\mathrm{n} F L_\mathrm{s} R^4}$$

The noise figure of the n:th amplifier stage is

$$F_n = \frac{S_\mathrm{in}/N_\mathrm{in}}{S_\mathrm{out}/N_\mathrm{out}} = \frac{1}{G_n} \frac{N_\mathrm{out}}{N_\mathrm{in}}$$

The overall noise figure is then given by Friis' formula (terms of -1 missing in book's equation (11.11))

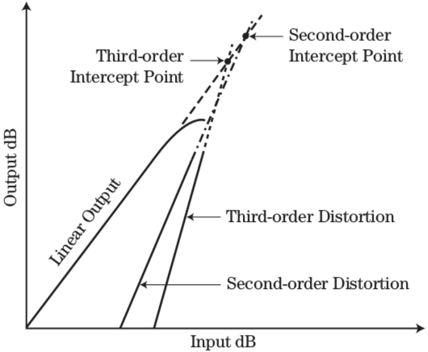
$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots$$

The noise bandwidth B_n is often taken as the final IF bandwidth.

Outline

Compression point, intercept point

FIGURE 11-20 ■ Receiver distortion versus input power intercept point.



The desired linear output of the amplifier is compromised by saturation and nonlinearities.

Discussion

Improving receiver dynamic range using STC

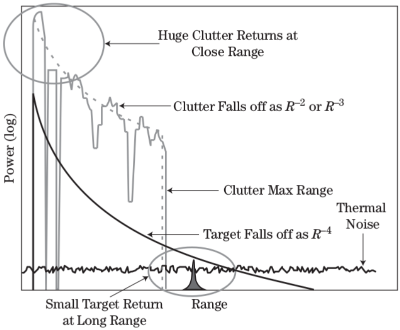
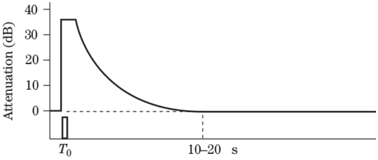


FIGURE 11-21 ■ Return signal amplitudes from targets and clutter.

FIGURE 11-22 ■ Sensitivity time control attenuation.

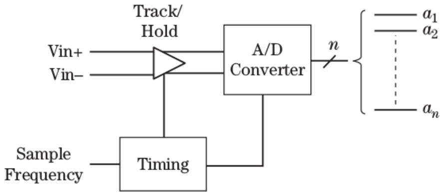


By introducing attenuation at early times, strong responses from near-range objects and clutter do not compromise dynamic range.

Outline

Typical ADC configuration

FIGURE 11-23 ■
Typical ADC configuration.



The track/hold circuit samples the signal and keeps its output constant until the analog to digital conversion is performed. The signal is then

$$V_{\mathrm{a}} = V_{\mathrm{FS}} \left(\sum_{i=1}^{n} a_i 2^{-i} \right) + q_{\mathrm{e}}$$

where V_{FS} is the full-scale voltage of the ADC, and q_{e} is the quantization error.

Examples of ADC:s

TABLE 11-1 ■ Sample of Analog-to-Digital Converters

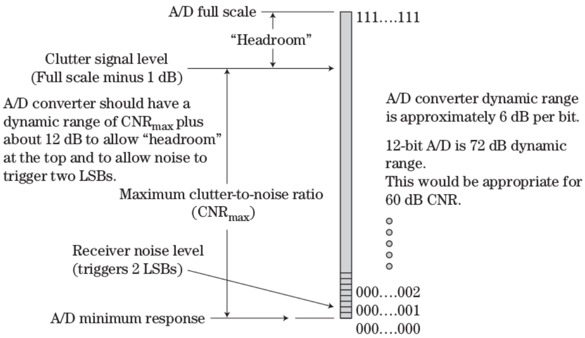
Part No.	Manufacturer	Bits	Sampling Speed Msamples/sec	SFDR[a] dBc	SNR dB
ADC083000	National Semiconductor	8	3,000	57	45.3
MAX19692	Maxim	12	2,300	68@1.2 GHz	NS
AT84AS004	Atmel	11	2,000	55	51
ADC081500	National Semiconductor	8	1,500	56	47
Model 366	Red Rapids[b]	2/8	1,500	57	47
TS860111G2B	Atmel	11	1,200	63	49[c]
ADC10D1000	National Semiconductor	10	1,000	66	57
MAX5890	Maxim	14	600	84@16 MHz	NS
MAX5888	Maxim	16	500	76@40 MHz	NS
Model 365	Red Rapids[b]	2/14	400	84	70
ADS62P49	Texas Instrument	14	250	85	73
LTC2208	Linear Technology	16	130	83	78
AD9446	Analog Devices	16	110	90	81.6

Note: NS, not specified.
[a]Spurious-free dynamic range.
[b]Dual sampler.
[c]Noise power ratio.

The ADC used in the lab was capable of about 100 000 samples/s (about 12 000 samples/s claimed using python).

Dynamic range of ADC:s

FIGURE 11-24 ■ Dynamic range of a signal-following ADC.



The full dynamic range of the ADC is not attainable, due to headroom to maximum level, and noise level.

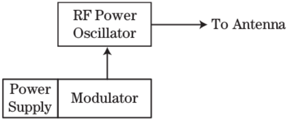
Outline

Conclusions

- Transmitters:
  - Two families of power sources: vacuum electronic devices, and solid state devices.
  - Three major components: 1) oscillator/power amplifier, 2) modulator, 3) power supply.
  - Incoherent (random startup) or coherent (reproducible startup).
  - Concentrated or distributed feed in array antennas.
- Receivers:
  - Incoherent and coherent receivers.
  - Demodulation: incoherent, coherent (I/Q).
  - Noise power: noise figure, multiple stages, bandwidth.
  - ADC: dynamic range reduced by clutter signal and noise level.

Discussion

FIGURE 10-3 ■ Free-running oscillator-based transmitter.

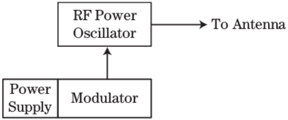


Why would the above configuration be deemed "incoherent"?

◂ Go back

Discussion

FIGURE 10-3 Free-running oscillator-based transmitter.



Why would the above configuration be deemed "incoherent"?

Answer: The only thing we can do with the RF power oscillator is to turn it on or off using the modulator, but the phase is out of control.

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Discussion

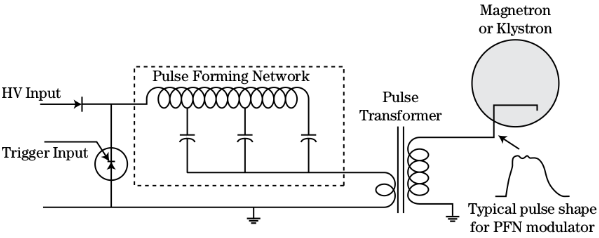

FIGURE 10-21 ■ Simplified diagram of a PFN modulator.

Why does the PFN produce two flanks (and not just one) of the RF pulse after the trigger input drains the energy from the PFN?

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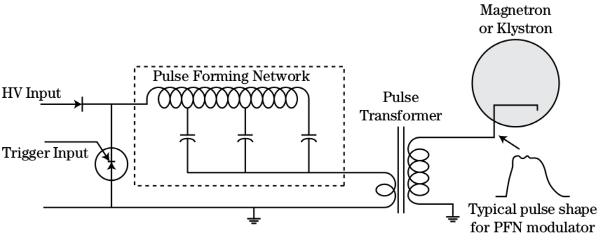

FIGURE 10-21 Simplified diagram of a PFN modulator.

Why does the PFN produce two flanks (and not just one) of the RF pulse after the trigger input drains the energy from the PFN?

Answer: The pulse transformer only reacts to time-varying currents. At the trigger input instance, the PFN is drained of energy and the pulse starts. Some time later, the PFN is again fully charged and no current is going through the transformer, putting a stop to the RF pulse.

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Discussion

Why is it important to down-converse the received signal (remove the carrier frequency)?

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Discussion

Why is it important to down-converse the received signal (remove the carrier frequency)?

Answer: Without down-conversion, we put extremely high requirements on the AD sampler circuit. At a lower IF or video frequency, these requirements can be considerably relaxed.

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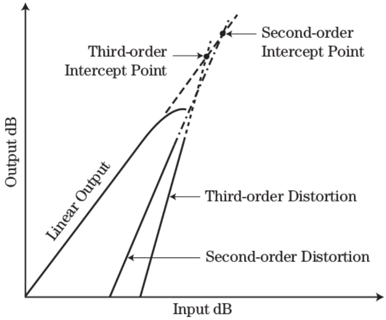
Discussion

FIGURE 11-20 Receiver distortion versus input power intercept point.



Is it possible to measure the intercept point directly, that is, setting the input dB to one certain value and read off the output dB corresponding to the intercept point?

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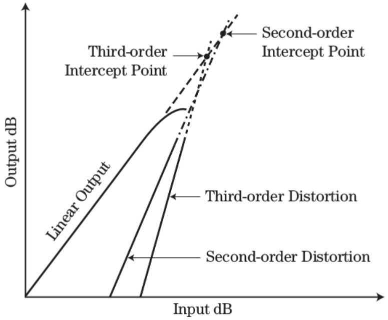
Discussion

FIGURE 11-20 Receiver distortion versus input power intercept point.



Is it possible to measure the intercept point directly, that is, setting the input dB to one certain value and read off the output dB corresponding to the intercept point?

Answer: No, the very concept of an intercept point is an asymptotic property which is never attained in a real system.

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