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RADAR ALTIMETERS
OVERVIEW OF OPERATION, DESIGN, AND PERFORMANCE

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PRESENTATION OVERVIEW

- This presentation will provide a general discussion of the following topics:
  - Basic Radar Altimeter Operation
  - System Block Diagram and Description
  - Radar Altimeter Installations
  - Radar Altimeter Transceivers and Signals
  - Signal Processing
  - Terrain Targets and Loop Loss Calculation
  - Sensitivity and Dynamic Range
- All block diagrams, descriptions, parameters, and characteristics provided are *typical*—there will always be exceptions.
- While this information is meant to give a general understanding of radar altimeter design and operation, actual implementations will vary significantly, especially when considering all use cases (for both civil and military applications).

INTRODUCTION TO RADAR ALTIMETERS

Physical Characteristics, Basic Operation, and Supported Aircraft Functions

WHAT IS A RADAR ALTIMETER?

- A radar altimeter (a.k.a. radio altimeter, Rad Alt, RALT) is a small, low-power, downward-looking radar ranging system which measures aircraft height above terrain and obstacles.
- Rad Alts are used on all types of civil and military aircraft, including transport and cargo airplanes, private airplanes, helicopters, combat aircraft, missiles, UAVs, etc.
- Typical transceiver SWaP: 50–400 in^3, 3–12 lb, 10–30 W (28 VDC or 115 VAC 400 Hz)
- Examples:

Civil/Commercial

Photo credit: Collins Aerospace

Photo credit: Garmin

Photo credit: Honeywell

Military

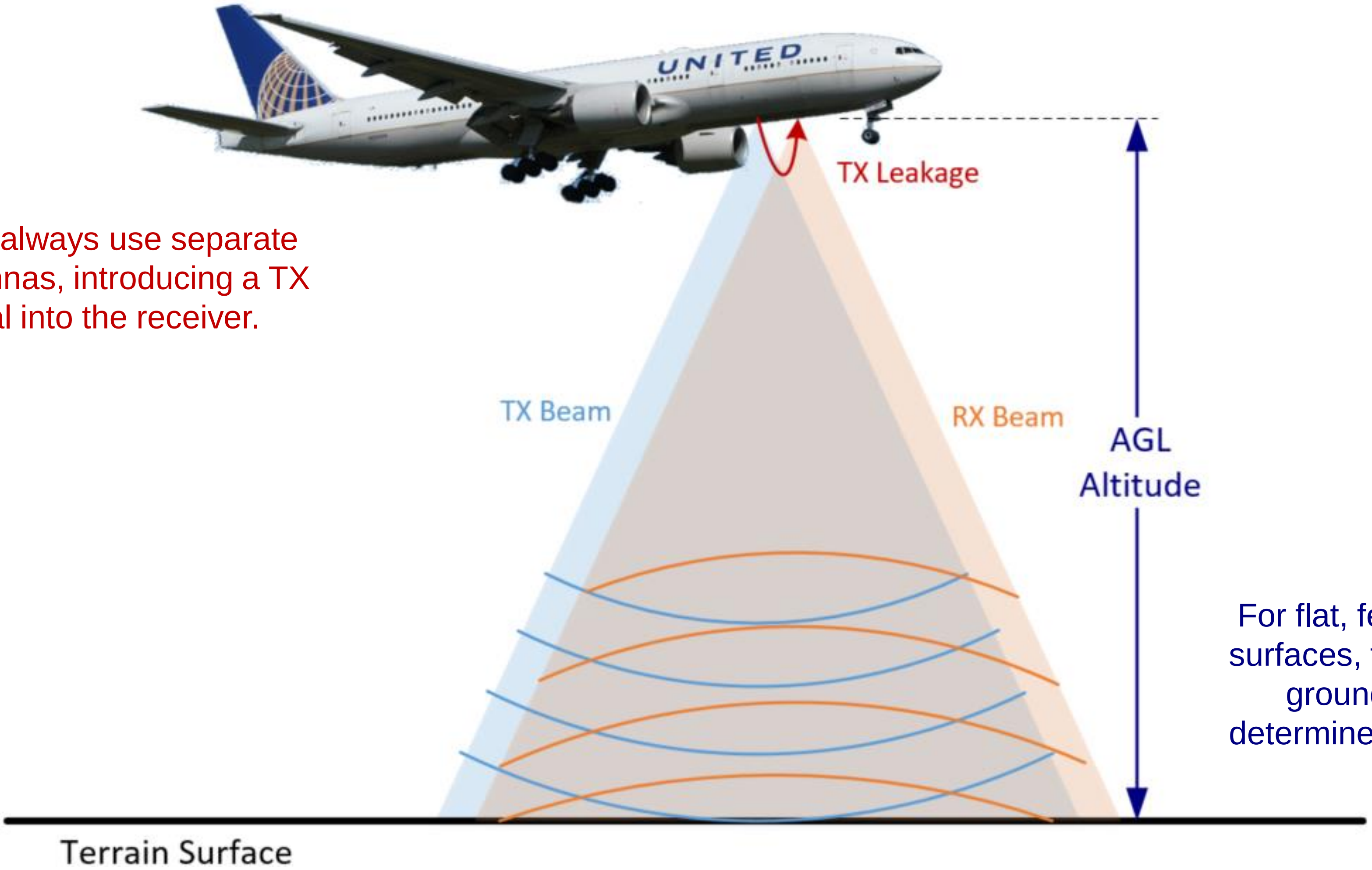
Photo credit: Honeywell

Photo credit: BAE Systems

Note: pictures not to scale

WHAT DOES A RADAR ALTIMETER DO?

Like any other radar system, a Rad Alt works by transmitting a signal toward the target (i.e. the terrain surface), receiving the reflected signal, and measuring time delay to determine distance to the target:

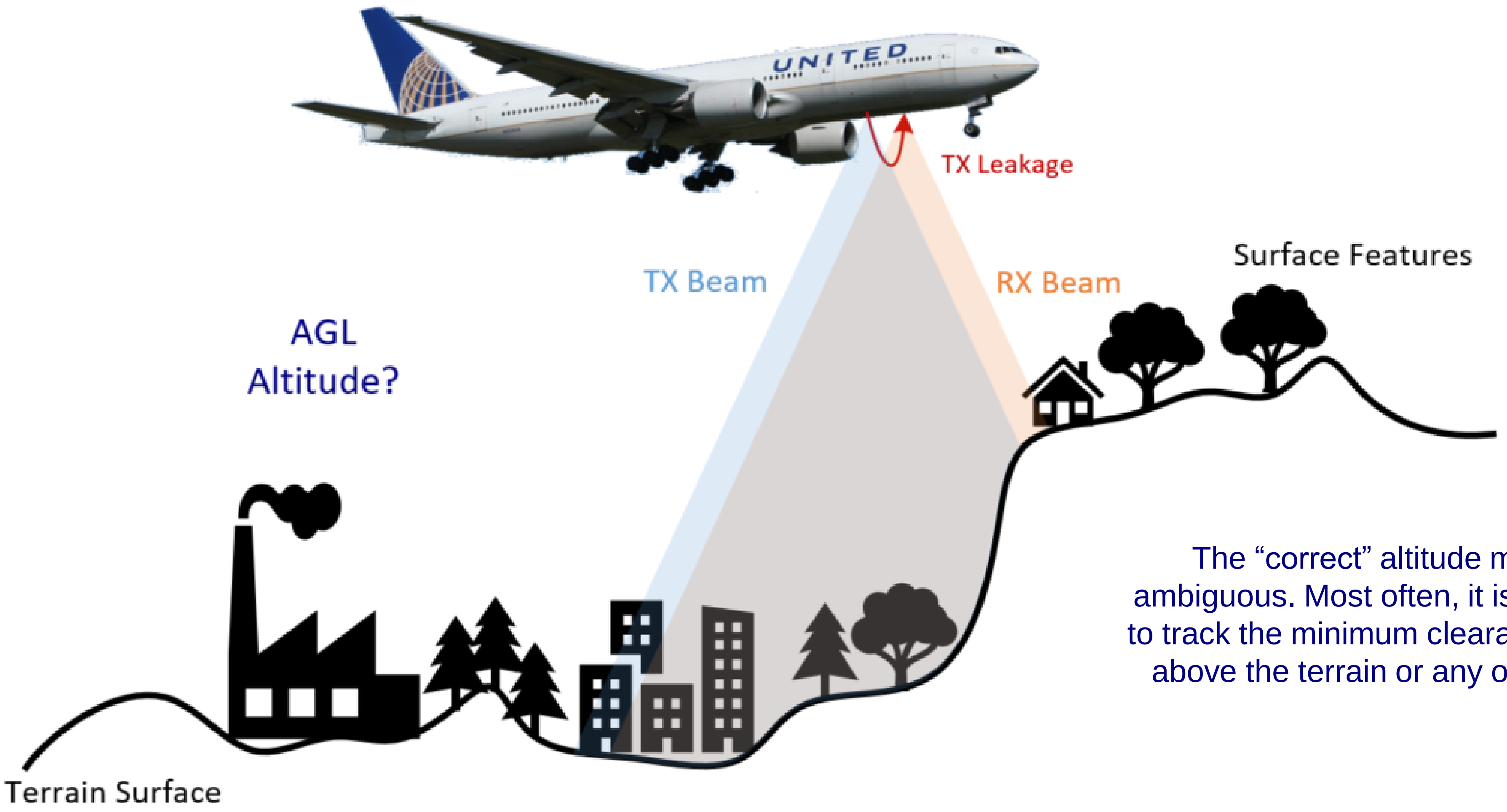


Rad Alts almost always use separate TX and RX antennas, introducing a TX leakage signal into the receiver.

For flat, featureless terrain surfaces, the altitude above ground level can be determined unambiguously.

WHAT DOES A RADAR ALTIMETER DO?

Most terrain surfaces are not flat and featureless. A more common scenario may look like this:



The “correct” altitude may be ambiguous. Most often, it is desirable to track the minimum clearance height above the terrain or any obstacles.

HOW ARE RADAR ALTIMETERS USED?

- Radar altimeters support a multitude of aircraft-level functions, including:
    - Situational awareness (pilot’s display of AGL altitude/minimum clearance height)
    - Terrain Awareness and Ground Proximity Warning Systems (TAWS/EGWPS)
    - Automated flight controls (autothrottle, automated landing flare, pitch/roll authority, etc.)
    - Vertical guidance on landings, including aural callouts (on both instrument and visual landings)
    - Traffic Collision Avoidance System (TCAS)
    - Mode controls and inhibiting for other systems (e.g. Predictive Windshear in weather radar)
- Some military applications have additional unique functions not applicable to civil aircraft:
    - Terrain following flight
    - Terrain-aided navigation

TYPICAL PERFORMANCE CHARACTERISTICS

Parameter	Civil/Commercial	Military
Maximum Reported Altitude	2,500 – 7,500 ft	1,500 – 50,000 ft
Altitude Accuracy	±1.5 ft to ±3 ft up to 100 ft AGL ±2% to ±3% from 100 to 500 ft AGL ±2% to ±5% above 500 ft AGL	±2 ft to ±4 ft up to 100 ft AGL ±2% to ±4% above 100 ft AGL
Aircraft Pitch and Roll Angles	±20° to ±40°	±20° to ±60°
Loop Sensitivity	Depends on terrain backscatter, antenna patterns, pitch/roll requirements, and RF cable losses	
Operating Temperature	-55°C to -40°C min. +70°C max.	-55°C to -40°C min. +70°C to +85°C max.
Other Operating Environments	DO-160() (ENV and EMI/EMC)	MIL-STD-810() (ENV), MIL-STD-461() (EMI/EMC)

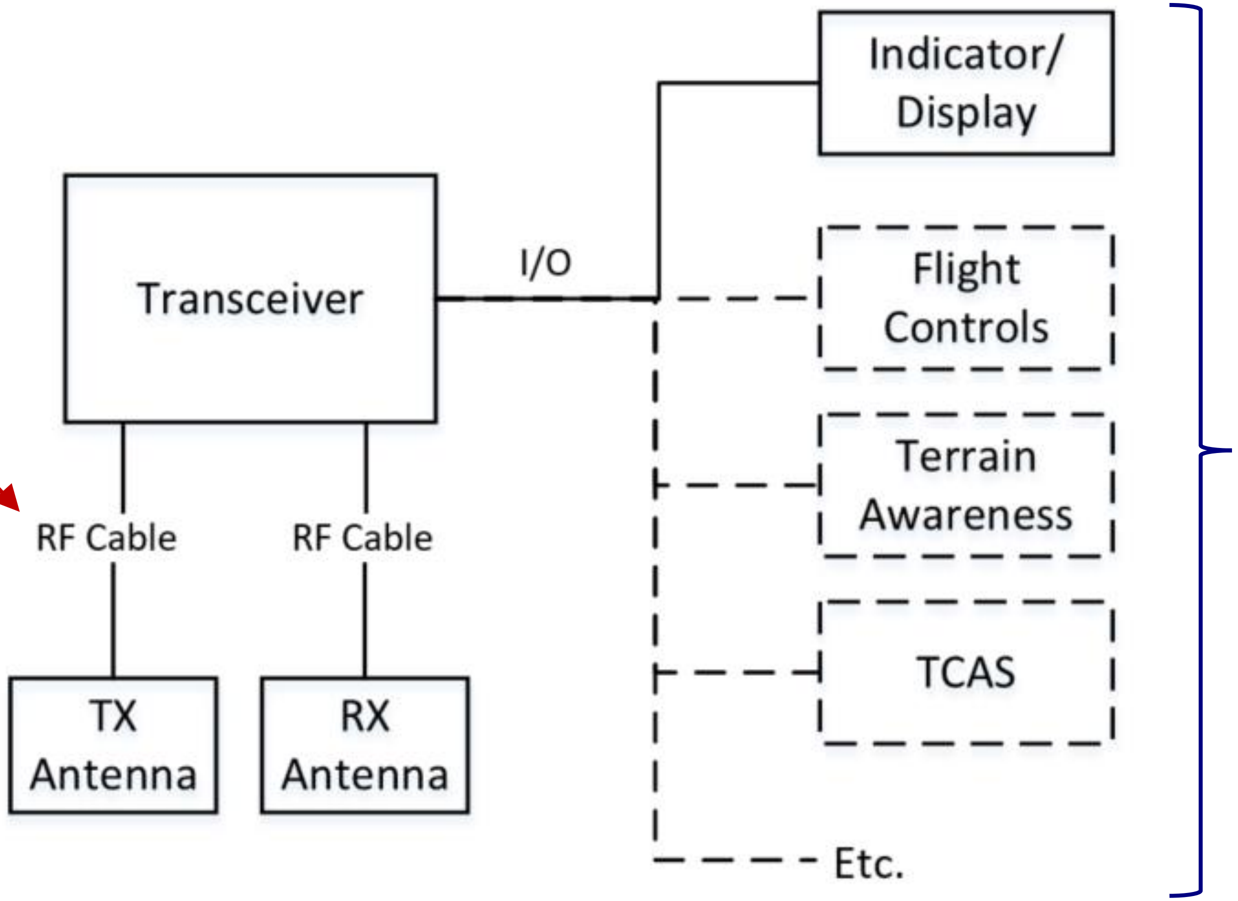
THE RADAR ALTIMETER SYSTEM

Components and Integration

SYSTEM BLOCK DIAGRAM

RF cables impart additional propagation delay and insertion loss in the signal path, both of which must be accounted for.

Antennas are fixed to the airframe and are not steered or gimballed. Therefore, wide beamwidths are necessary to ensure sufficient FOV even with aircraft pitch/roll maneuvers.



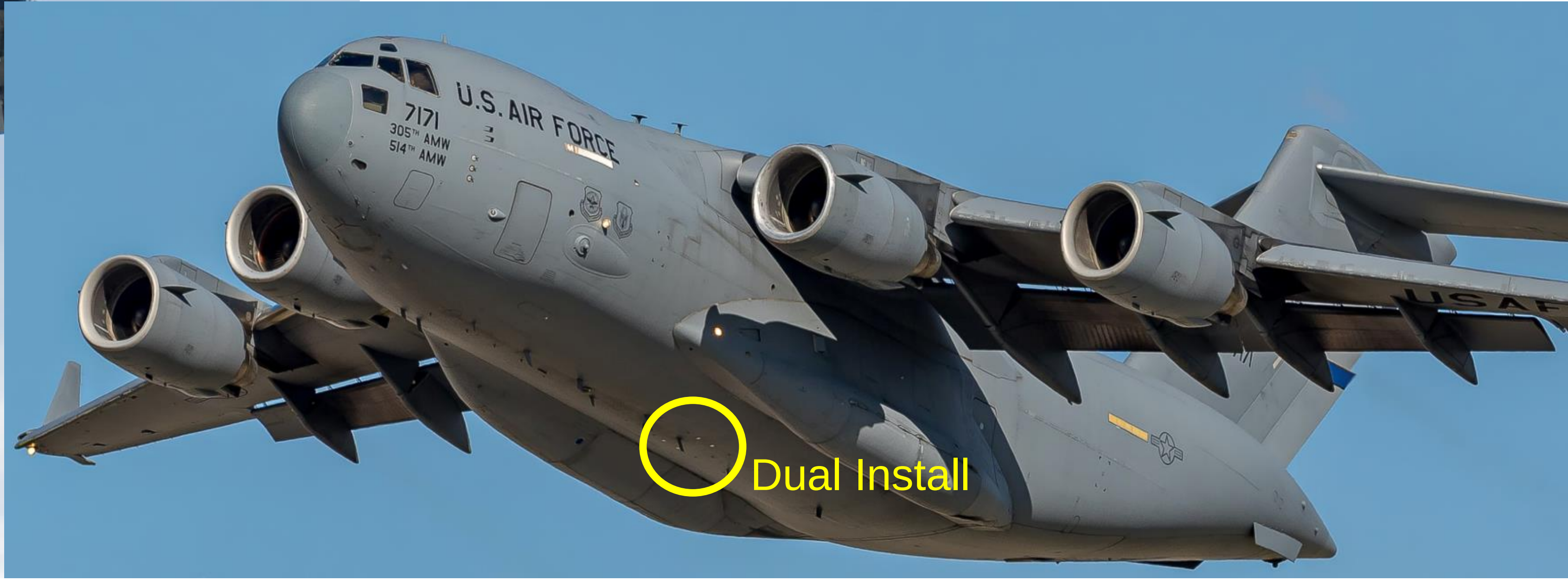
Output to various downstream systems depends on specific aircraft integration.

Different levels of integration are possible—for example, an indicator integrated into the transceiver unit.

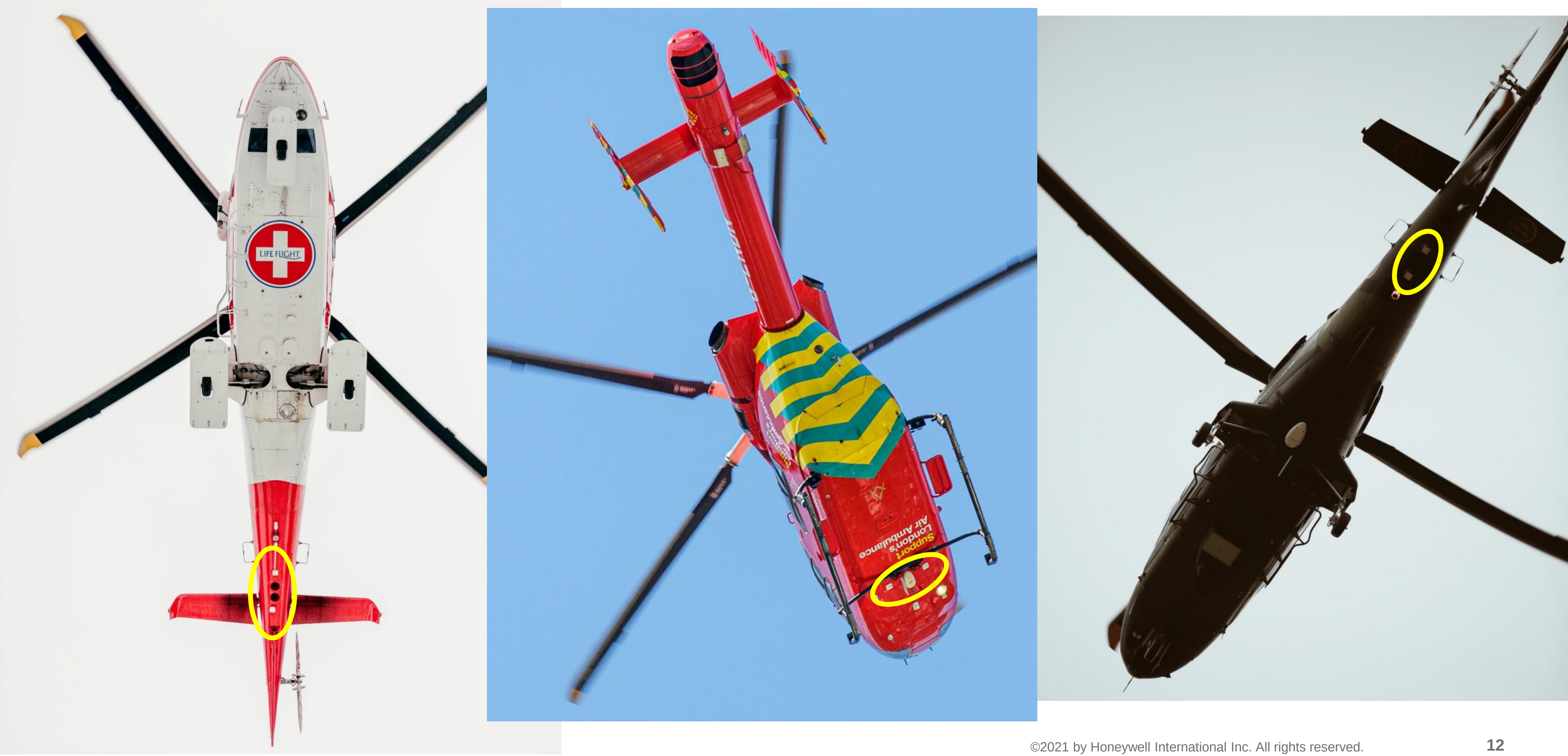
RADAR ALTIMETER INSTALLATIONS

Antenna Placement and Characteristics, RF Cable Losses, and Multiplex Installations

EXAMPLE INSTALLATIONS: FIXED-WING



EXAMPLE INSTALLATIONS: HELICOPTERS



TYPICAL ANTENNA CHARACTERISTICS

- Linearly polarized microstrip patch antennas are most common for all applications.
- Form factors: approx. 4” x 4” square, or approx. 6” diameter circle
- Peak gain at 4.3 GHz: 7–13 dBi (10–11 dBi is most common)
- 3 dB beamwidth at 4.3 GHz: ±20° to ±45°
  - Wider beamwidths used for aircraft with large roll angle requirements, e.g. single-seat fighters.
- TX-RX separation distance: 18” to 48”
- TX-RX isolation: 75–100 dB (85–90 dB is most common)
- Cross-system isolation in multiplex installations: 60–90 dB
- Installation orientation: typically have TX-RX pairs H-plane coupled.
  - If TX-RX pairs are installed fore-and-aft, H-plane will be along aircraft longitudinal axis, and E-plane will be along aircraft lateral axis.
  - If TX-RX pairs are installed side-by-side, H-plane will be along aircraft lateral axis, and E-plane will be along aircraft longitudinal axis.
  - Fore-and-aft installations are generally more common.

TYPICAL RF CABLE CHARACTERISTICS

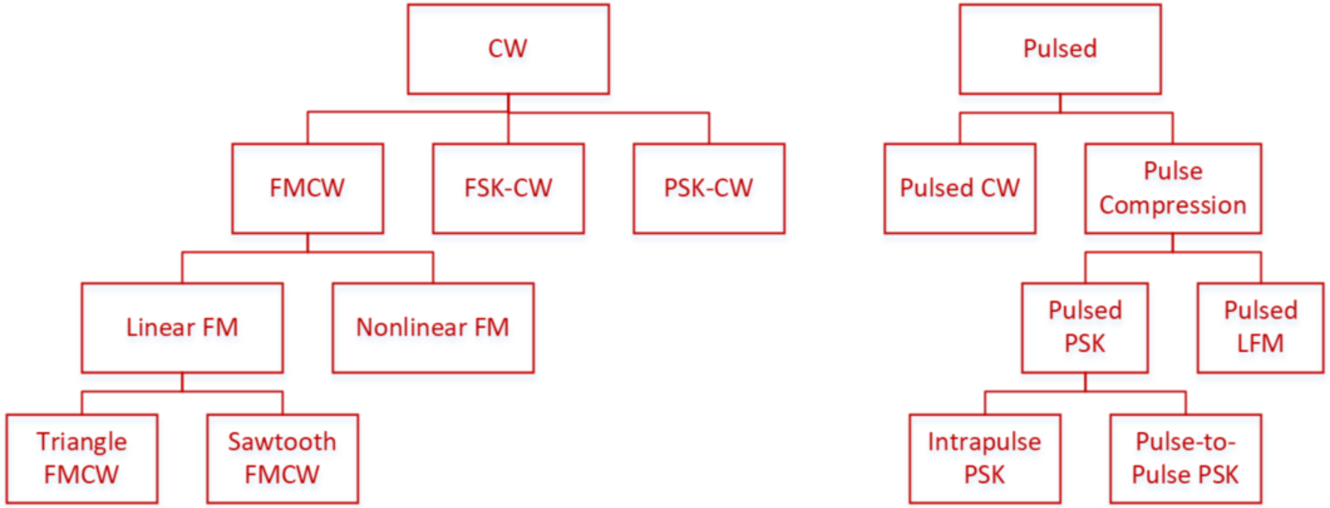
- The vast majority of Rad Alts use antennas which are external to the transceiver unit, with separate TX and RX antennas.
  - Thus, RF transmission lines are needed between the transceiver and the antennas—generally coaxial cables.
- RF cable lengths and coaxial cable types can vary substantially for different installations on different aircraft types.
- Typical RF cable lengths: 10–50 ft total (TX+RX)
- Typical RF cable losses: 4–10 dB total (TX+RX)
- Although smaller aircraft (e.g. helicopters) usually have shorter cable runs, they also typically use higher-loss cable which is cheaper, lighter, and easier to install.
  - As a result, even small aircraft can have comparable RF cable losses to much larger aircraft.

RADAR ALTIMETER TRANSCEIVERS OVERVIEW

Modulation Schemes, RF Architectures, and Transmitter & Receiver Characteristics

MODULATION AND WAVEFORMS

- Rad Alts can use a variety of different modulation schemes—any waveform suitable for ranging can work:



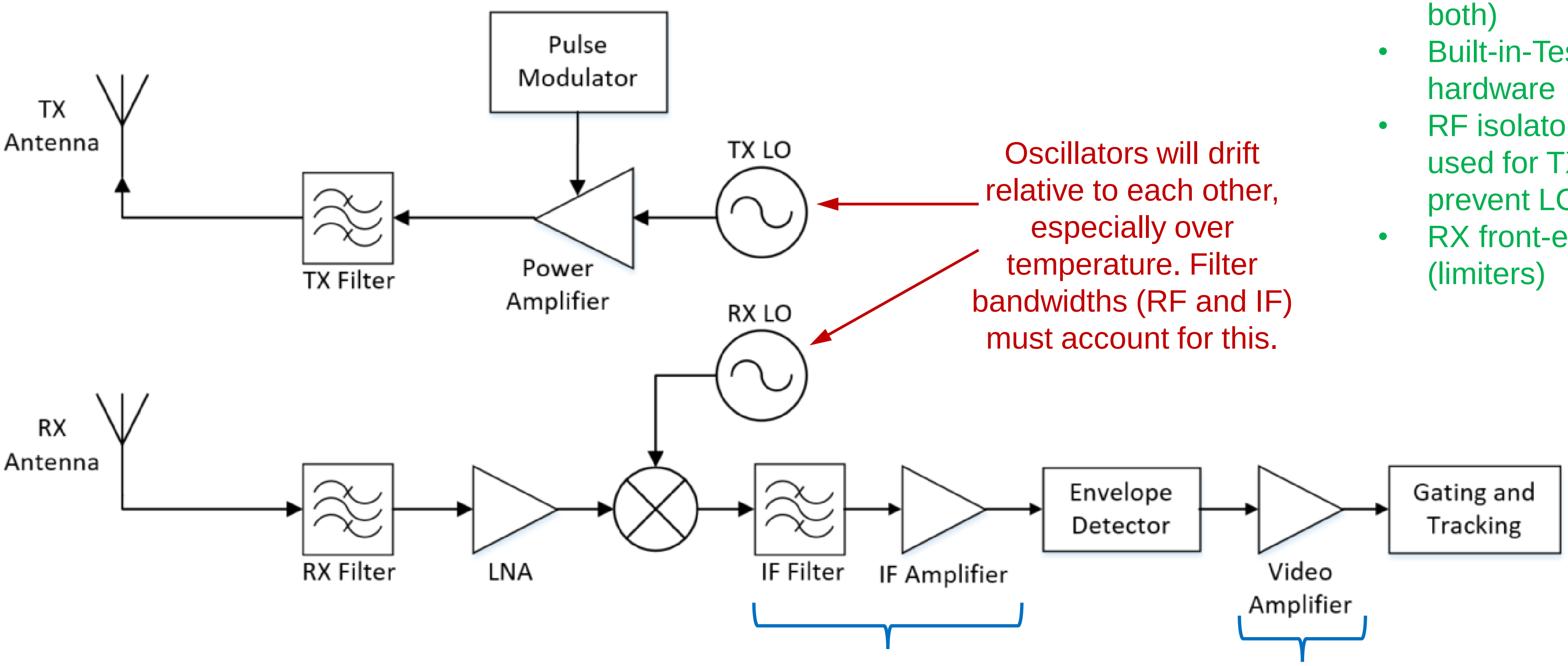
- Frequency Hopping (FH) can also be applied on top of various other modulation schemes.
- Note that Rad Alts with any digitally-coded modulation scheme or FH (that is, any spread-spectrum methods other than LFM/FMCW) are export control restricted (ITAR).
- Most civil/commercial Rad Alts use linear FMCW modulation, but some use pulsed CW as well.
- Most military Rad Alts use pulsed CW modulation, but there are some PSK pulsed, PSK CW, and FMCW Rad Alts as well. Many military Rad Alts also employ Frequency Hopping.

NONCOHERENT HETERODYNE ARCHITECTURE

(Noncoherent Pulsed CW Rad Alts)

Not Shown:

- PMC
- AGC/NAGC (could be implemented at RF, IF, or both)
- Built-in-Test (BIT)/Monitoring hardware
- RF isolators (sometimes used for TX protection and to prevent LO reradiation)
- RX front-end protection (limiters)



Oscillators will drift relative to each other, especially over temperature. Filter bandwidths (RF and IF) must account for this.

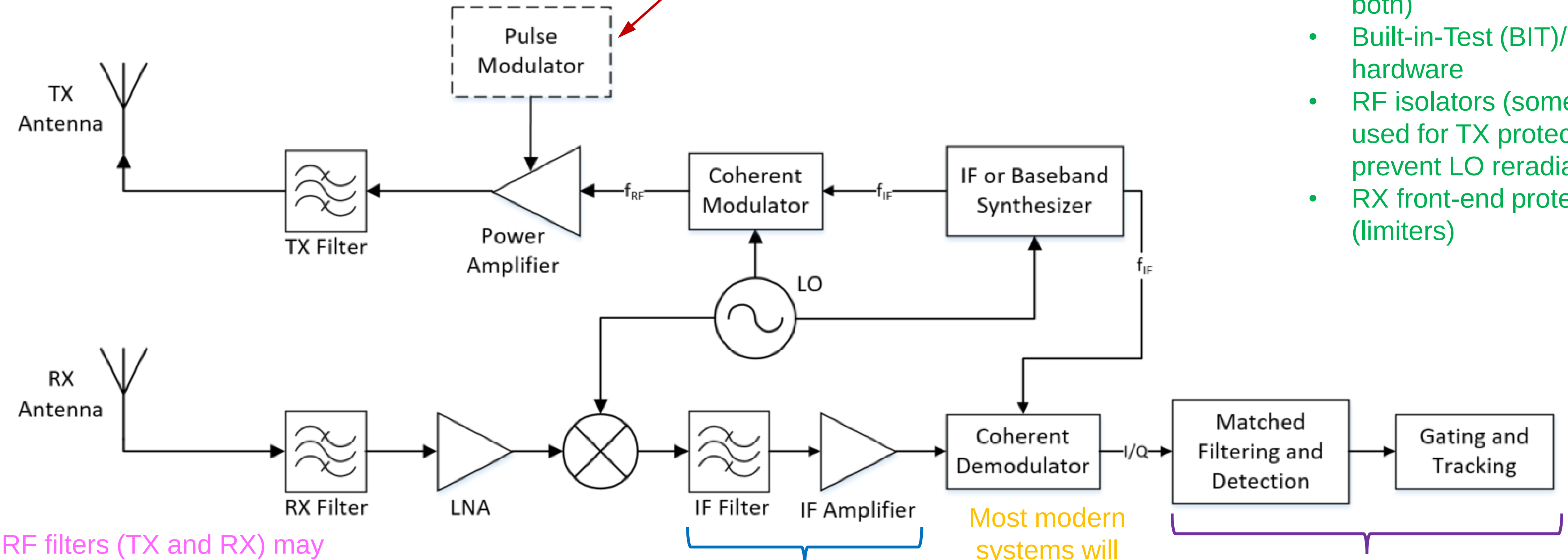
IF and Video/Baseband may each have multiple gain and filtering stages.

COHERENT HETERODYNE ARCHITECTURE

(Coherent Pulsed CW & Pulsed or CW PSK Rad Alts)

Not Shown:

- PMC
- AGC/NAGC (could be implemented at RF, IF, or both)
- Built-in-Test (BIT)/Monitoring hardware
- RF isolators (sometimes used for TX protection and to prevent LO reradiation)
- RX front-end protection (limiters)



Pulse modulator not used for modulated CW.

RF filters (TX and RX) may have wide bandwidth and slow roll-off to minimize insertion loss and phase distortion.

IF may have multiple gain and filtering stages.

Most modern systems will directly sample IF signal and perform downstream processing digitally.

Gating may take place prior to matched filtering/detection.

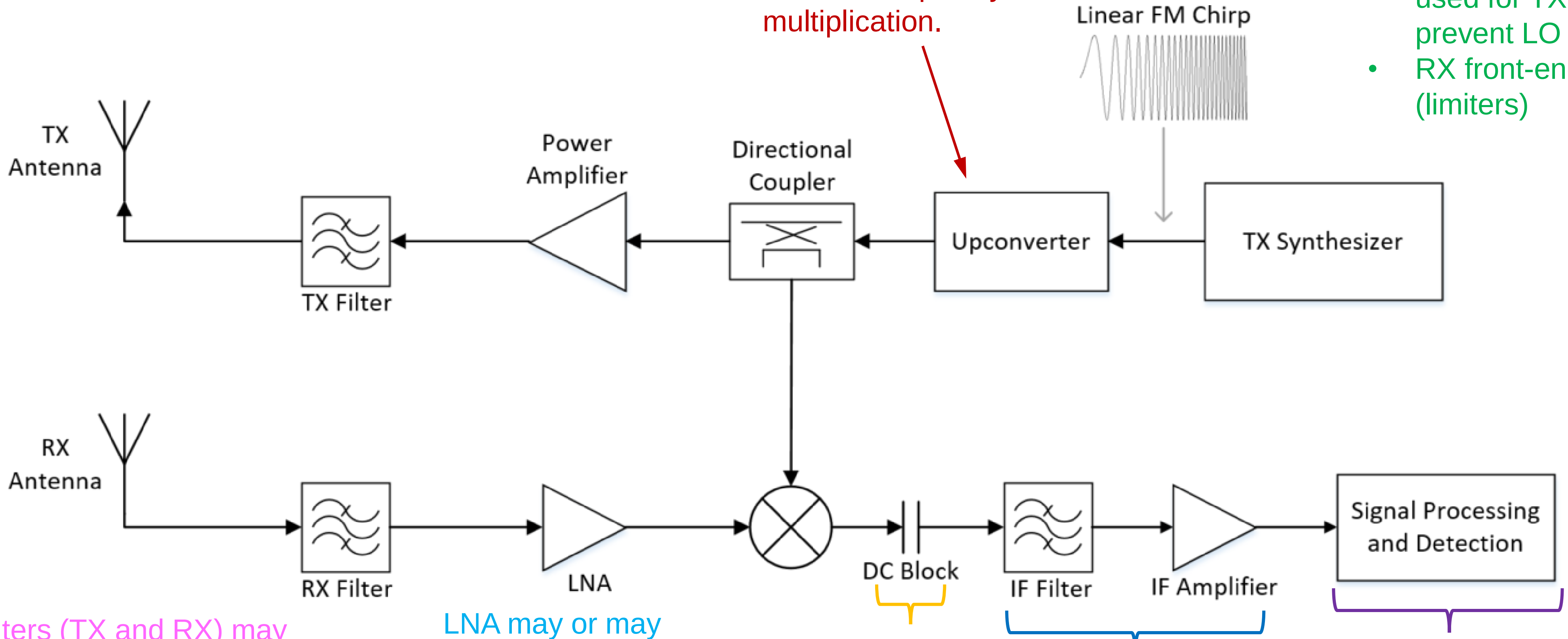
HOMODYNE ARCHITECTURE

(FMCW Rad Alts)

Not Shown:

- AGC/NAGC (could be implemented at RF, IF, or both)
- Built-in-Test (BIT)/Monitoring hardware
- RF isolators (sometimes used for TX protection and to prevent LO reradiation)
- RX front-end protection (limiters)

Upconversion may use modulator or frequency multiplication.



RF filters (TX and RX) may have wide bandwidth and slow roll-off to minimize insertion loss and phase distortion.

LNA may or may not be present ahead of mixer.

DC block helps reject TX leakage.

IF may have multiple gain and filtering stages.

Modern designs evaluate baseband spectrum with FFT; older designs may use frequency counters.

TYPICAL TRANSCEIVER CHARACTERISTICS

Parameter	FMCW	Pulsed
Transmitter		
Peak TX Power	0.05 – 2 W	1 – 10 W[1]
TX Pulse Width	N/A	20 ns – 20 μs[2]
Pulse Repetition Interval[3]	N/A	10 – 200 μs
Sweep Bandwidth	100 – 180 MHz	N/A
Sweep Period	0.2 – 10 ms	N/A
Receiver		
IF Frequency	N/A	20 – 80 MHz
IF Bandwidth	0.2 to 2 MHz (single-sided)	10 – 50 MHz
Detector Bandwidth	0.1 – 10 kHz	0.1 – 50 kHz

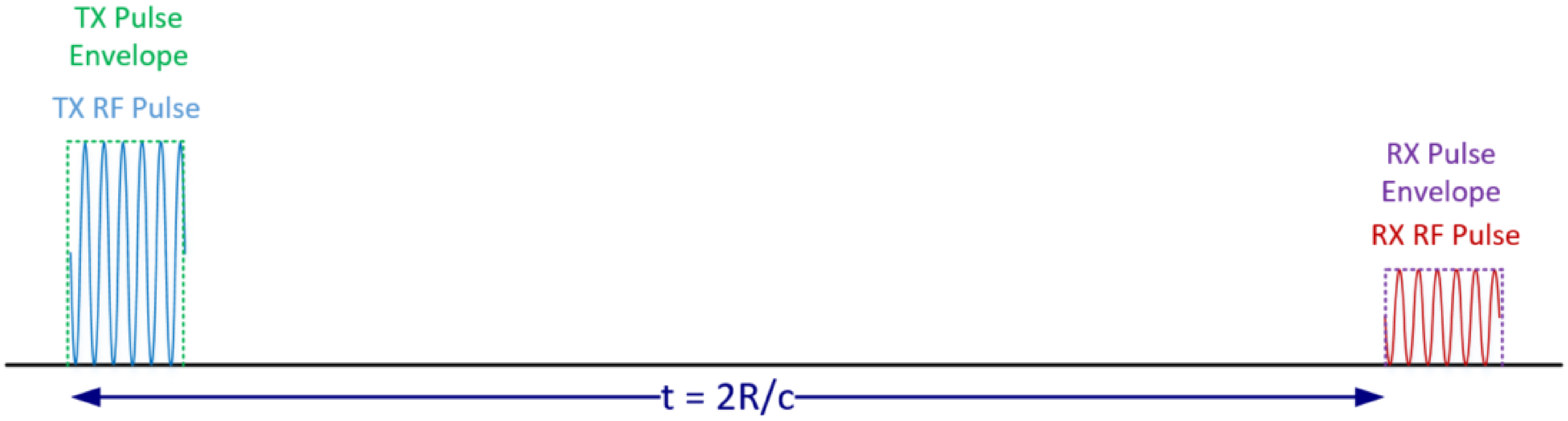
1. Many military Rad Alts use active Power Management Control (PMC) to reduce TX power to the minimum necessary to maintain a stable altitude track. This feature is not available for civil/commercial Rad Alts (ITAR restricted).
2. Max. pulse width is typically a few microseconds, except for pulse compression systems or systems with very high maximum altitude.
3. PRI is typically pseudorandomly dithered (PRI jitter) to prevent mutual interference.

RADAR ALTIMETER SIGNALS

Pulsed CW, Pulse Compression, and FMCW Signal Characteristics

PULSED CW TX AND RX SIGNALS

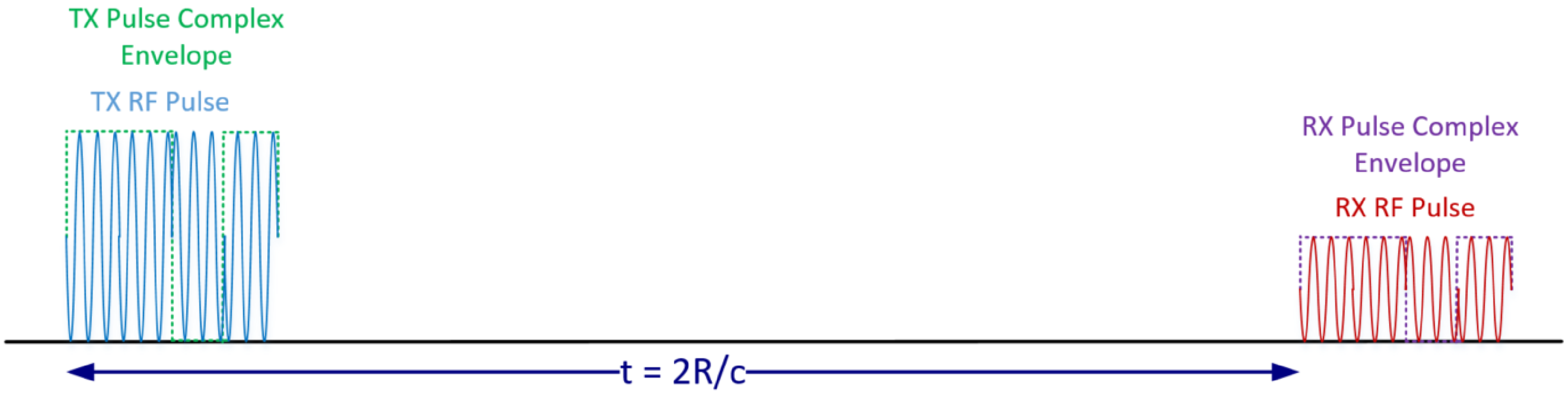
For a single point target, the received signal is simply a delayed and attenuated copy of the transmitted signal. If the target is at a range R from the radar, then the time delay is t = 2R/c.



The attenuation of the received signal is dictated by the radar equation, discussed later.

PULSE COMPRESSION TX AND RX SIGNALS

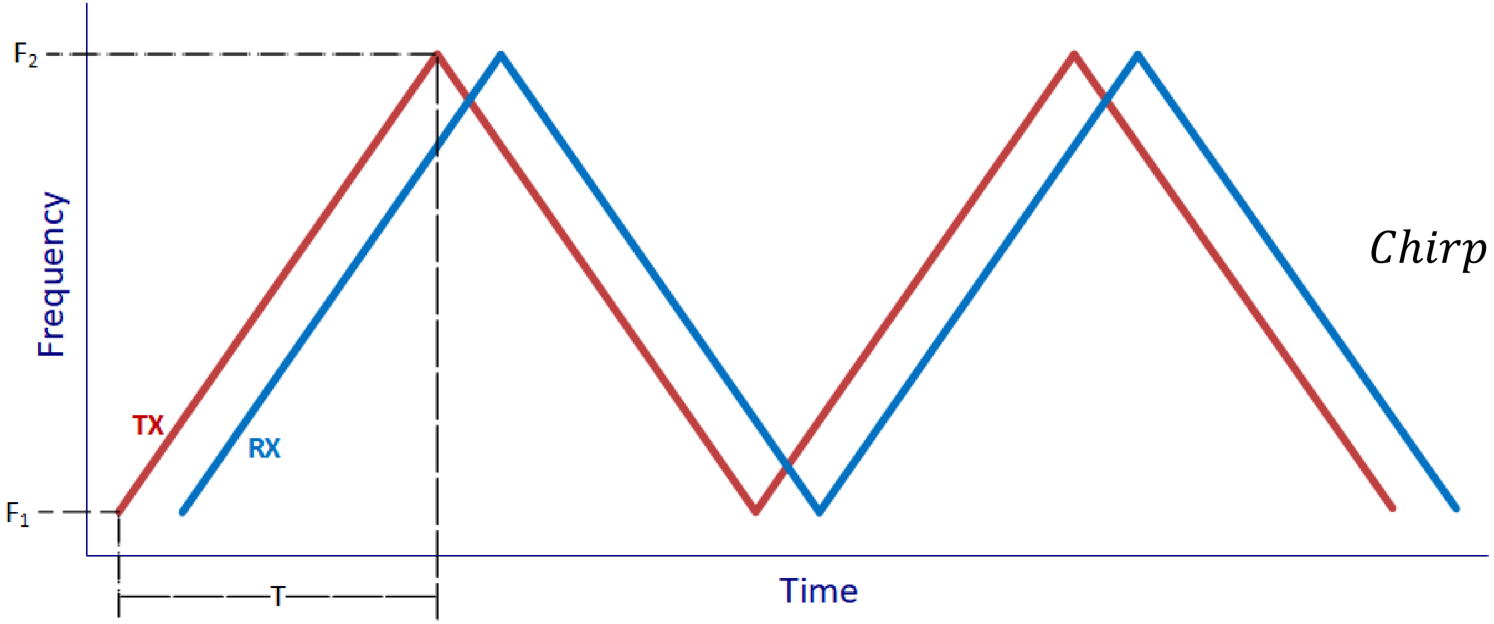
With additional modulation of pulses, and coherent matched filtering in the receiver, longer pulse widths can be used (which improves sensitivity) without sacrificing range resolution (which is key to accuracy).



Fine range resolution can be maintained with pulse compression, since range resolution is inversely proportional to the signal bandwidth. This is equivalent to spread-spectrum methods in other types of radio systems.

FMCW TX AND RX SIGNALS

FMCW Rad Alts are functionally equivalent to LFM pulse compression systems, but the coherent matched filtering process can be efficiently implemented with a homodyne transceiver architecture.



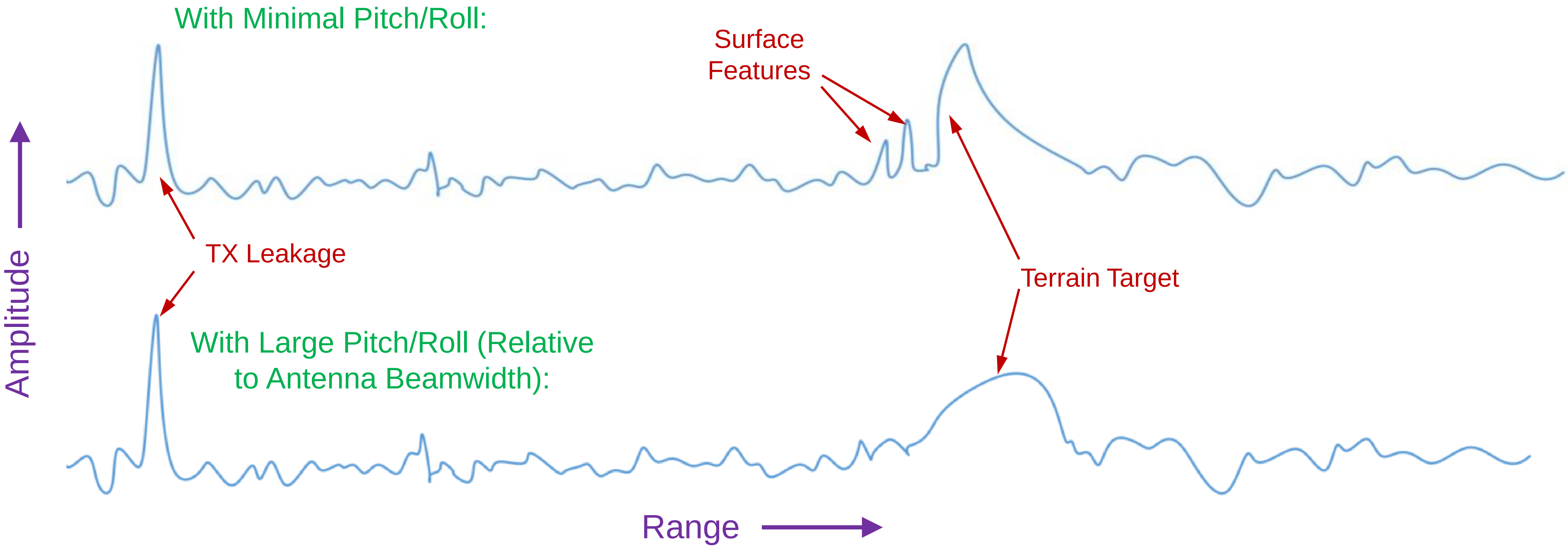
$$Chirp\ Rate:\ K = \frac{Sweep\ Bandwidth}{Sweep\ Time}$$

The RX time delay (and thus target range) is directly proportional to the baseband signal frequency: $\boxed{f_b = K\frac{2R}{c}}$

The RX waveform is also shifted due to Doppler, but triangle FMCW allows for range-Doppler decoupling.

VIDEO/BASEBAND SIGNALS

The baseband signal (at the output of the detector or matched filter) is what the receiver processes to detect and track terrain targets (and measure altitude). Because the terrain is not a point target, the baseband signal is more complicated than a simple delayed copy of the TX envelope. There is also RX noise and TX leakage:



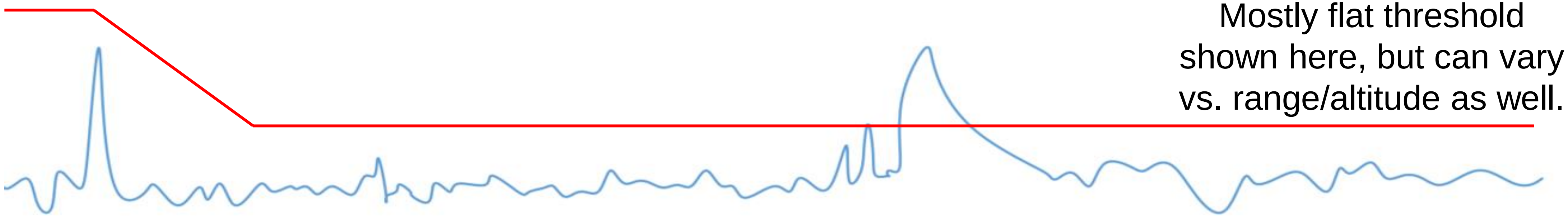
In FMCW altimeters this corresponds to the baseband frequency domain, otherwise it is the baseband time domain.

RADAR ALTIMETER SIGNAL PROCESSING

Detection, Acquisition & Tracking, and
Altitude Determination

THRESHOLD DETECTION

Detection of targets in the baseband signal typically uses some form of threshold detection, with a threshold set at some SNR (typically around 7–13 dB) to achieve desired false alarm and missed detection probabilities (based on assumed noise and target statistics):



Mostly flat threshold shown here, but can vary vs. range/altitude as well.

At close-in ranges, threshold may be set to avoid TX leakage, rather than based on a specific SNR.

Detection processing may be done on only a portion of the baseband signal at a time, for example using one or more signal *gates*.

In some implementations, thresholds may not be dynamically set based on a fixed detection SNR, but predetermined based on received power levels.

ACQUISITION AND TRACKING

- Due to signal fading, terrain targets may not satisfy detection criteria on every single pulse or FMCW chirp. This may be handled in a few ways:
  - Target validation, where targets at a given range are only considered valid if detections occur on a certain percentage of pulses or chirps over some time interval.
  - Averaging the baseband signal over many pulses or chirps prior to detection processing.
  - Validation or averaging intervals typically span a few milliseconds to tens of milliseconds.
- The process of first identifying a terrain target through detection and validation, either after initial power-up or after a loss of lock, is called *acquisition*.
- After a valid terrain target is identified, it will be *tracked* as long is it continues to meet the detection and validity criteria.
- To avoid oscillations at the sensitivity limit, there is typically hysteresis employed in the thresholds and validity criteria used for tracking vs. acquisition.
- Often, multiple “targets” at many different ranges will meet the detection and validity criteria. Generally, Rad Alts seek to track the valid target at the lowest range, corresponding to the minimum clearance height of the aircraft.

ALTITUDE CALCULATION AND FILTERING

- Once a valid terrain target is identified, altitude is calculated based on some aspect of the target's range profile—usually the *leading edge* or the *centroid*.
- Individual altitude measurements can be noisy due to fading, intermittent detection of some surface features, aircraft dynamics, etc., so the values are typically filtered before being output.
- The amount of filtering which can be applied (e.g. the filter cutoff frequency/bandwidth) is limited based on dynamic tracking requirements.
- For civil/commercial aircraft, the performance standard indicates a **maximum** step response time constant of 100 milliseconds.
- For military aircraft, performance specifications often include maximum tracking rate requirements (usually a few thousand feet per second).
  - Note that this corresponds to terrain closure rate, not just aircraft dynamics alone.
- Filter bandwidths are usually on the order of a few Hz to tens of Hz.
- Altitude update rates on external data buses are typically 10–60 Hz.

RADAR ALTIMETER TARGETS

Terrain Scattering and Loop Loss Calculation

RADAR EQUATION FOR A POINT TARGET

As mentioned earlier, with a point target the received signal is a delayed and attenuated copy of the transmitted signal:

$$P_{RX}(t) = \frac{P_{TX}\left(t - \frac{2R}{c}\right) G^2 \lambda^2 \sigma}{64\pi^3 R^4}$$

$P_{RX}(t) =$ Received power as a function of time (t = 0 is start of TX pulse)

$P_{TX}(t) =$ Transmitted power as a function of time (TX power envelope)

$R =$ Range (one-way distance) from radar to target

$c =$ Speed of light in air

$G =$ Antenna gain in direction of target (assuming same patterns for TX and RX, approximately co-located)

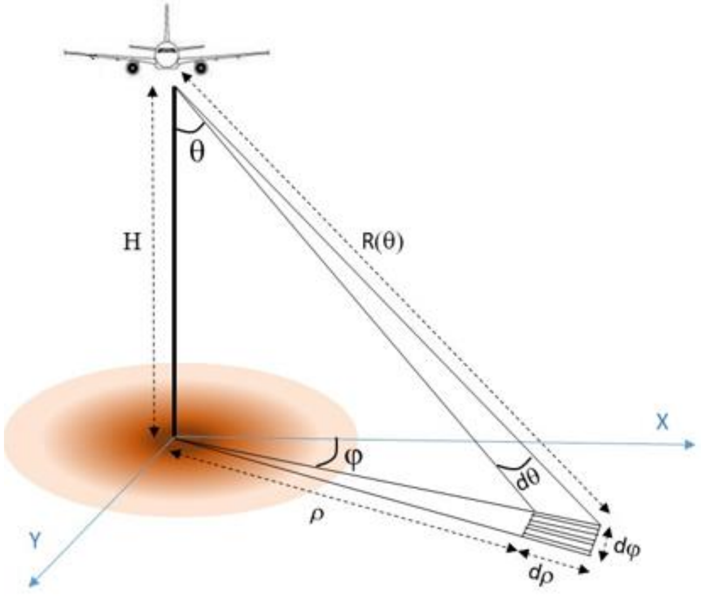
$\lambda =$ RF wavelength

$\sigma =$ Radar cross section

DISTRIBUTED TARGETS

Distributed targets, like a terrain surface, consist of many independent scattering centers. With sufficient relative motion between the radar platform and the terrain, the various scattering centers will have uniformly distributed random phases, producing noise-like fading statistics.

Because of the independent, uniformly distributed phases, the received power contributions from different portions of the terrain can be integrated to yield an ensemble average for the received power envelope from the entire terrain surface [1].



The mean scattering, and the fading statistics, of a particular terrain surface can be described by a statistical model of the *backscatter coefficient* σ_0. This is equivalent to the radar cross section normalized per unit area and is a function of the incidence angle θ.

DISTRIBUTED TARGET RX POWER ENVELOPE

Peak TX power

Minimum height above terrain surface

$$\overline{P_{RX}(t)} = \frac{p_{tx}\lambda^2}{64\pi^3H^2}\int_0^{\pi/2}\int_0^{2\pi} \underbrace{F\left(t-\frac{2H}{c}\sec\theta\right)} \underbrace{G(\theta,\varphi)^2} \underbrace{\sigma_0(\theta,\varphi)} \sin\theta\cos\theta\, d\varphi\, d\theta$$

F(t) is the *point spread function*, which is the radar system response to an ideal point target (after detection or matched filtering). For a noncoherent pulsed CW radar, it is equal to the TX pulse envelope. For coherent pulsed or modulated CW radar, it is the square magnitude of the autocorrelation function of the transmitted baseband waveform. There may also be a factor for pulse shaping or windowing functions, if these are used.

Antenna pattern (power gain), in coordinate frame fixed to terrain surface. If aircraft has nonzero pitch or roll, a coordinate transformation using a rotation matrix is needed.

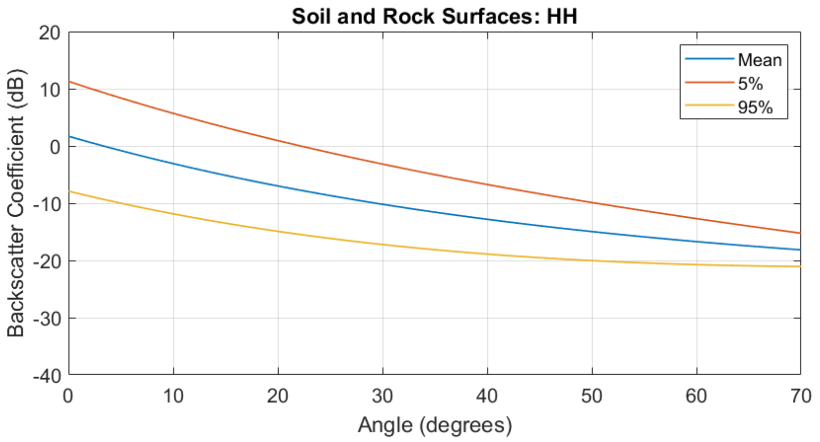
Terrain backscatter coefficient as a function of incidence and azimuth angles

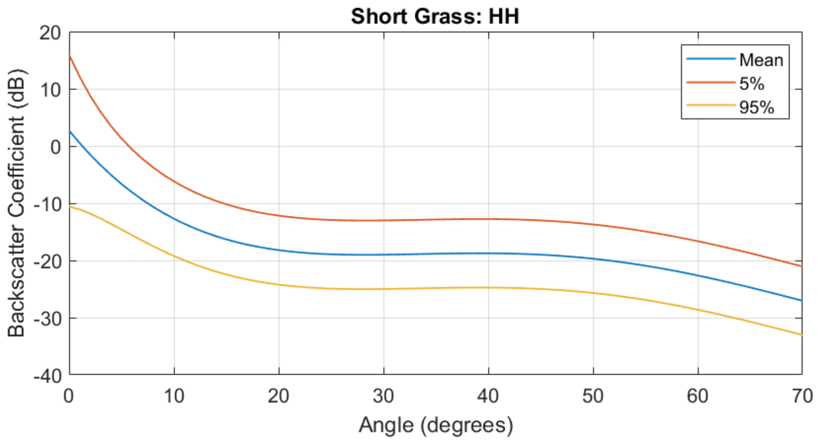
Azimuth angle

Incidence angle

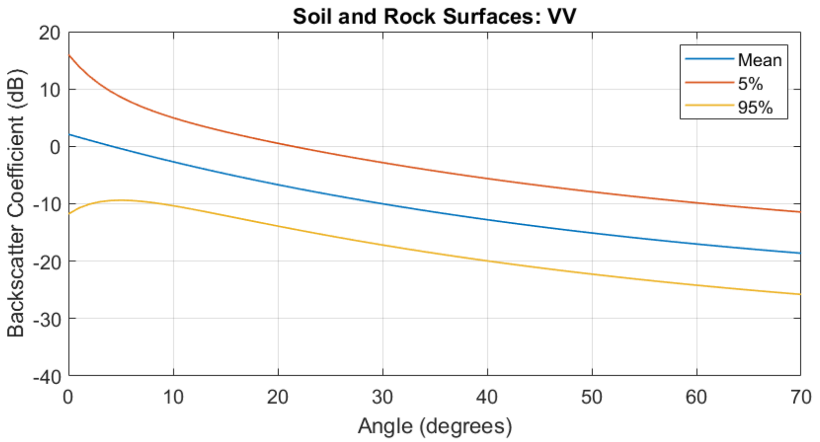
EXAMPLE TERRAIN SCATTERING MODELS

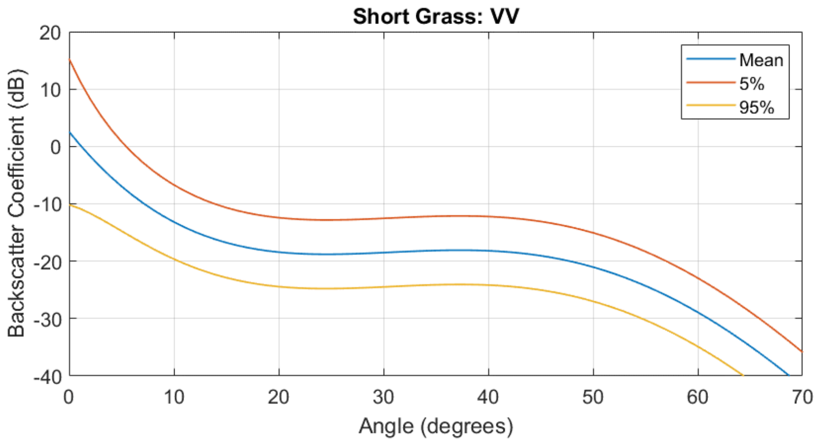
Terrain scattering models derived from empirical data are available in literature. For example, the following C-band models from Ulaby and Dobson [2]:





Blue line indicates mean, while orange and yellow lines show 90% confidence interval based on fading statistics.



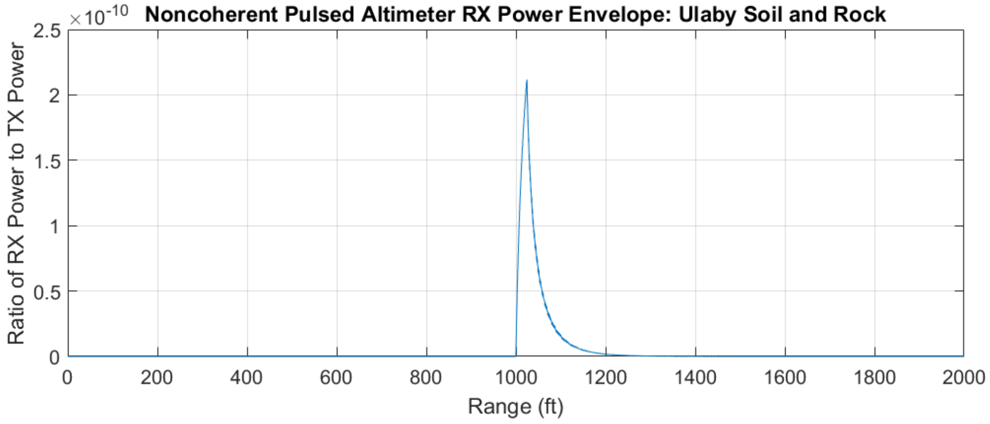


GENERAL TERRAIN CHARACTERISTICS

- Very smooth (relative to RF wavelength) terrains which are not lossy can exhibit nearly specular reflection, with very high backscatter near vertical incidence, but rapid roll-off at steeper angles.
  - Calm water and ice
  - Some types of snow (depending on moisture content and pack density)
  - Some paved surfaces
- Terrains densely packed with vegetation or other irregular features or with varied or lossy surfaces will be much more diffuse, with lower peak backscatter and little dependence on incidence angle.
  - Forests or dense vegetation
  - Mountainous areas
  - Rocky or sandy deserts
- Many common terrains fall in between these extremes:
  - Residential and industrial areas
  - Most types of crops/farmland
  - Grasses and short vegetation

EXAMPLE RECEIVED POWER ENVELOPES

Using the Ulaby Soil and Rock terrain model from earlier (horizontal polarization case), the following mean received power envelopes are obtained at an altitude of 1000 ft with no pitch or roll (using 10 dBi antennas with ±25° beamwidth):

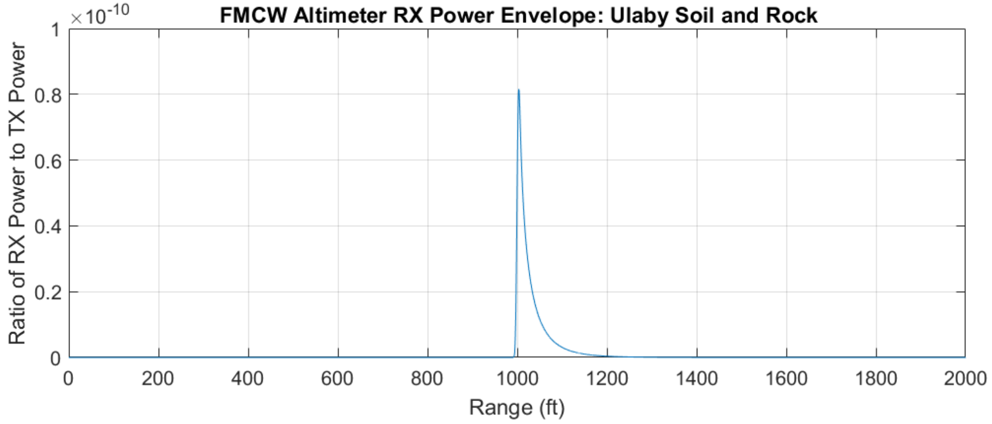


Noncoherent Pulsed CW Rad Alt

- Pulse width = 50 ns
- Rectangular TX pulse envelope

FMCW Rad Alt

- Sweep bandwidth = 100 MHz
- Sweep period = 1 ms
- Hamming window on receive



These received power envelopes are a model of the mean video/baseband signal without noise or TX leakage.

RELATIONSHIP TO LOOP LOSS

- *Loop loss* is the power ratio (or difference in dB) of the transmitted and received signals.
  - May be specified in reference to the TX and RX antenna ports (*external loop loss*), or in reference to the TX and RX ports on the transceiver (*total loop loss*).
- Loop loss can be calculated using the received power envelope as follows:

$$L(t) = -10\log_{10}\left[\frac{\overline{P_{RX}(t)}}{p_{tx}}\right]$$

- Generally, the loop loss at the peak of the received power envelope is of most interest.
- This formula yields external loop loss—to obtain total loop loss (for example, to define *loop sensitivity* requirements for a Rad Alt transceiver, or to configure test equipment to represent a particular set of operating conditions), RF cable losses must be added.

DO-155 LOOP LOSS

- For civil/commercial Rad Alts, the performance standards used for FAA certification refer to the loop loss calculation methods from RTCA DO-155 to define loop sensitivity requirements.
- DO-155 presents simplified algebraic formulas to approximate loop loss curves vs. altitude which encompass a range of operating conditions, without explicitly accounting for fading, pitch/roll, etc.
  - This allowed for much easier loop loss analysis at the time DO-155 was developed (1960s).
- Because of the multiple assumptions and simplifications made, correlating DO-155 loop losses with specific operating conditions (e.g. terrain backscatter, pitch/roll, etc.) is not straightforward.

FMCW Formula:

$$L = -10\log_{10}\left[\frac{G\lambda^2\sigma_0(0)M(H)V^*(H)}{16\pi^2H^2}\right]$$

G = **Peak** antenna gain
$\sigma_0(0) = 0.006$
$M(H)$: Accounts for limited pitch/roll below 100 ft
$V^*(H)$: Accounts for partial TX/RX antenna pattern overlap at very low altitudes (<10–15 ft)

Pulsed Formula:

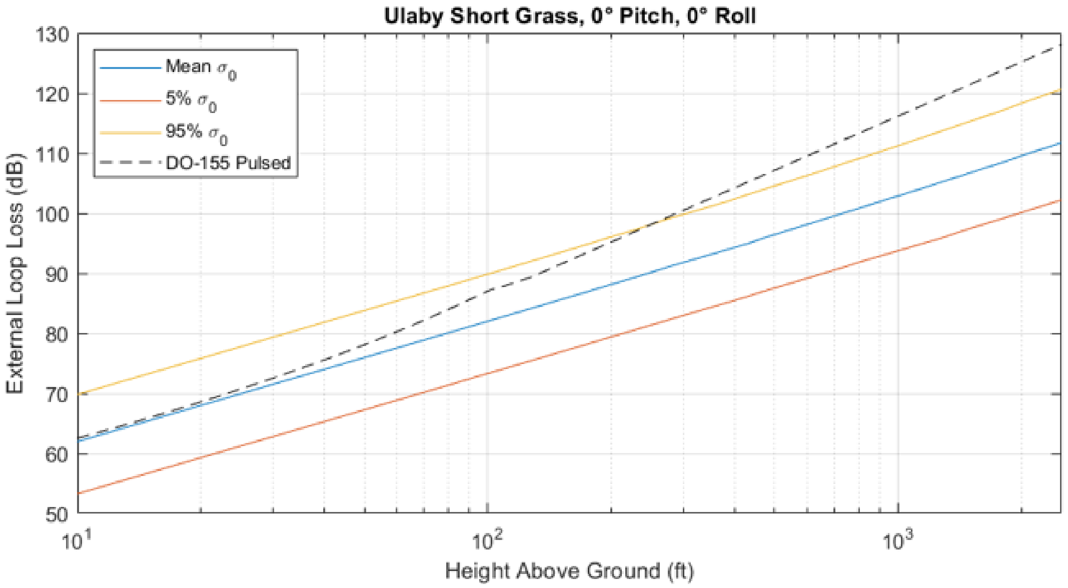
Extrapolate from FMCW formula as $\propto \frac{1}{H^3}$ above the critical height:

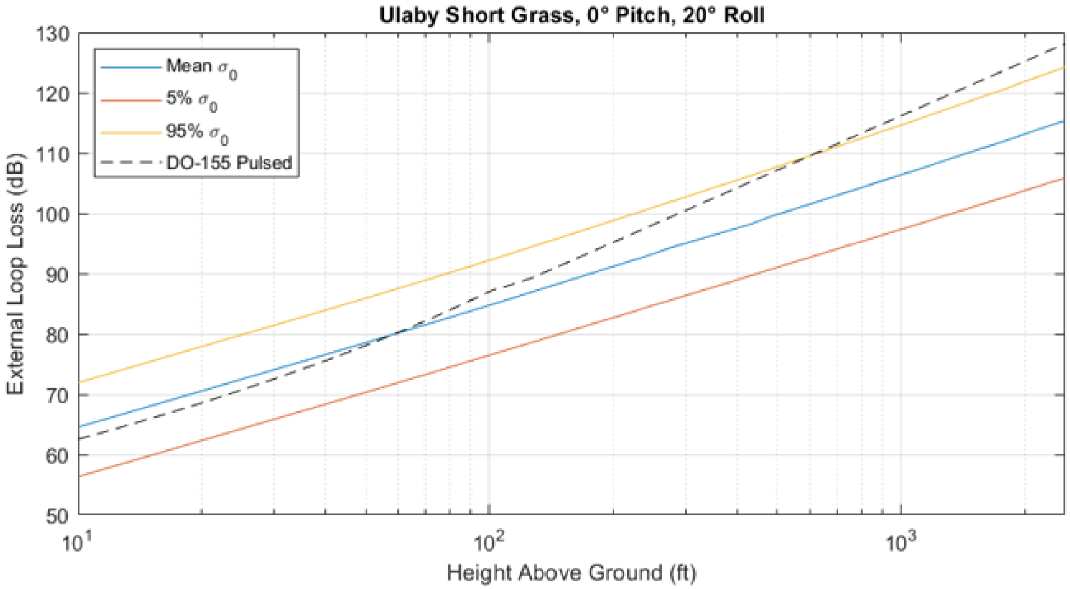
$$H_c = \frac{c\tau G}{4}$$

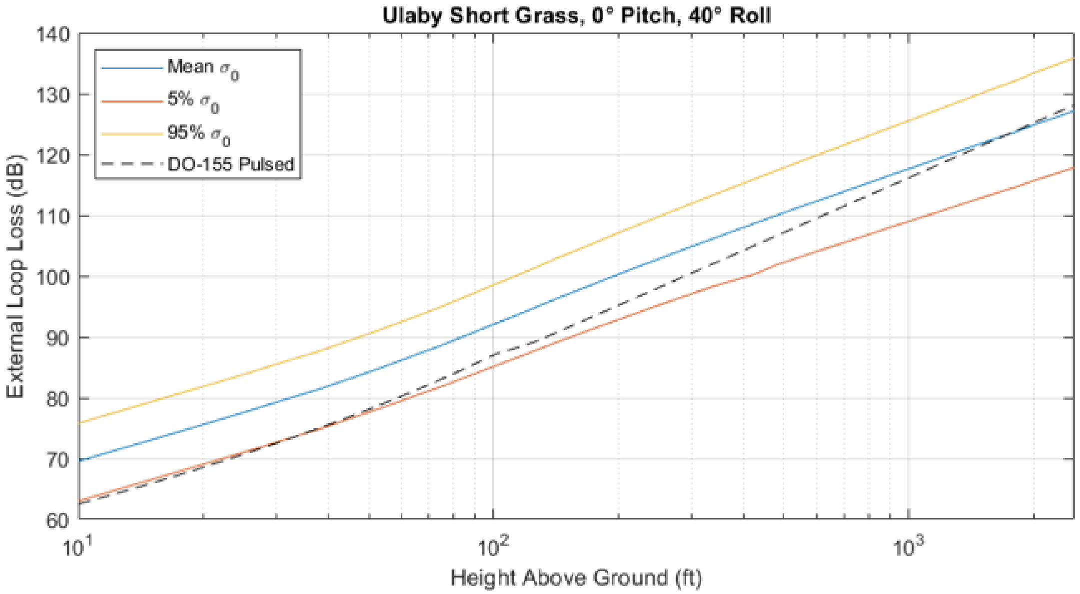
τ = Pulse width
G = **Peak** antenna gain

EXAMPLE LOOP LOSS CURVES: PULSED

For the same noncoherent pulsed CW Rad Alt example from earlier, with Ulaby Short Grass:

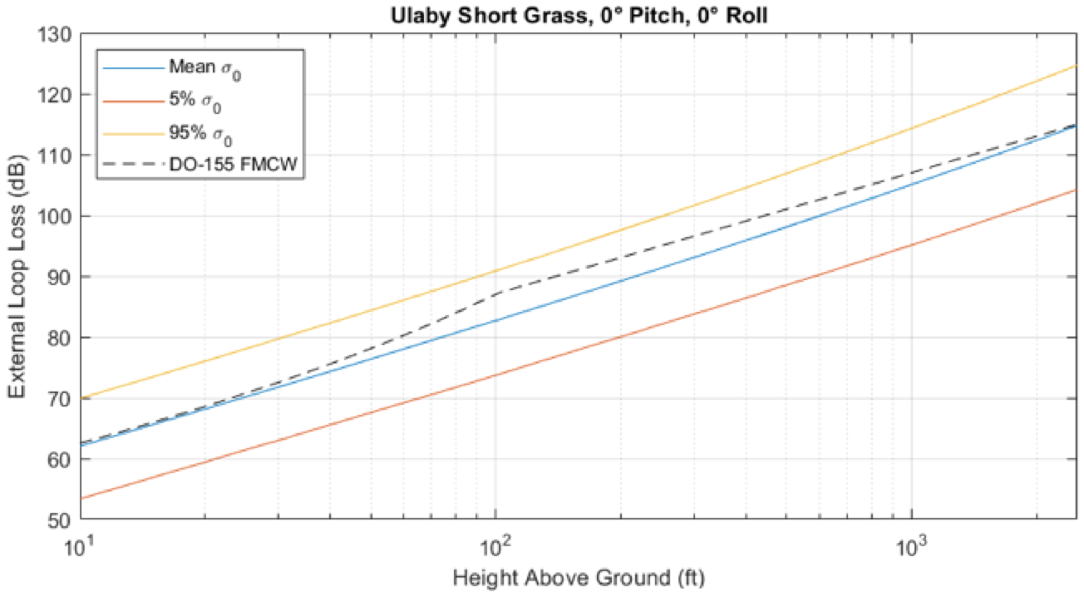

Ulaby Short Grass, 0° Pitch, 0° Roll

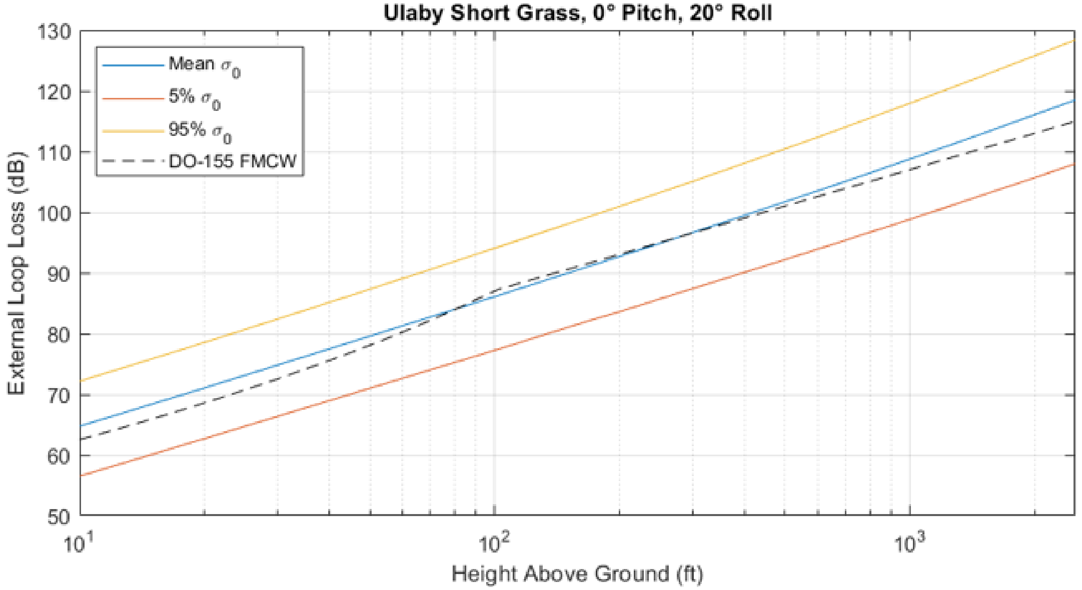

Ulaby Short Grass, 0° Pitch, 20° Roll

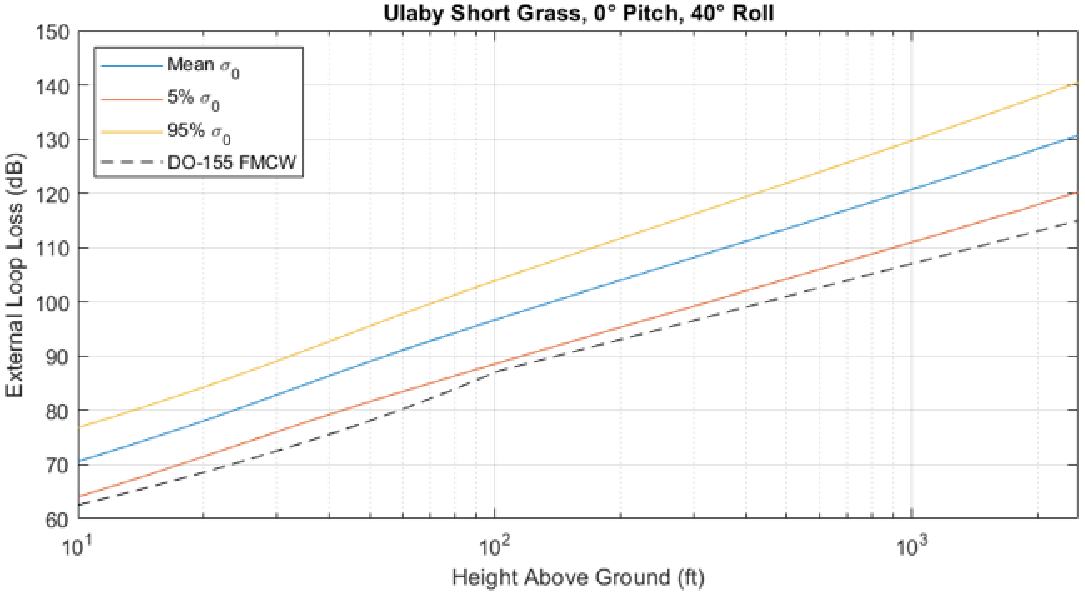

Ulaby Short Grass, 0° Pitch, 40° Roll

EXAMPLE LOOP LOSS CURVES: FMCW

For the same FMCW Rad Alt example from earlier, with Ulaby Short Grass:







RADAR ALTIMETER SENSITIVITY

Performance Characteristics vs. Altitude, and Dynamic Range Considerations

DYNAMIC RANGE

- Due to the significant variation in loop loss (and thus received signal levels) associated with different terrains, signal fading, aircraft maneuvering, and propagation loss vs. altitude, Rad Alts may need to accurately process and track signals over a dynamic range well beyond **100 dB**.
- Because the biggest contributor to this dynamic range is loop loss variation vs. altitude, the entire dynamic range does not need to be instantaneous or available for signals at every altitude.
- Therefore, the vast majority of Rad Alts will have sensitivity characteristics which are highly dependent on the range/altitude of the received signal.
- In FMCW Rad Alts, sensitivity vs. altitude is set primarily by tuning the baseband frequency response—more gain at higher frequencies provides more sensitivity for higher altitudes.
- In pulsed or other modulated CW Rad Alts, one or more of the following are typically used:
  - Sensitivity Range Control (SRC)
  - Automatic Gain Control (AGC)—either signal based or noise based (NAGC)
  - Variable transceiver characteristics vs. tracked altitude—including one or more of pulse width/TX bandwidth, IF or detector bandwidths, TX power, gate widths, detection/validity criteria, averaging intervals
    - Parameters may be varied continuously or in discrete steps.
    - Usually results in tradeoff with range resolution and accuracy.

LOOP SENSITIVITY CHARACTERISTICS

- The *loop sensitivity* of a Rad Alt is one of the most critical top-level performance characteristics. It defines the maximum loop loss at which the Rad Alt can still meet its intended function.
- Loop sensitivity can be specified in terms of acquisition/make-track sensitivity, or tracking/break-track sensitivity.
  - *Make-track sensitivity* is the maximum loop loss (and thus lowest RX power level) at which the Rad Alt can first acquire and begin tracking a signal at a particular altitude, starting from a non-tracking state.
  - *Break-track sensitivity* is the maximum loop loss (and thus lowest RX power level) at which the Rad Alt can continue tracking a signal at a particular altitude, while in a tracking state.
- Due to the acquisition/tracking hysteresis described earlier, break-track sensitivity is typically a few dB higher than make-track sensitivity.
- Loop sensitivity can also be expressed in terms of TX power and receiver sensitivity, as follows:

$$Loop\ Sensitivity\ (dB) = TX\ Power\ (dBm) - Receiver\ Sensitivity\ (dBm)$$

  - This receiver sensitivity value corresponds to an actual make-track or break-track condition, and thus it includes the detection SNR (unlike a Minimum Detectable Signal which only specifies the noise floor).

REFERENCES

REFERENCES AND FURTHER READING

1. R. K. Moore and C. S. Williams, “Radar Terrain Return at Near-Vertical Incidence,” in Proceedings of the IRE, vol. 45, no. 2, pp. 228-238, Feb. 1957, doi: 10.1109/JRPROC.1957.278394.
2. Ulaby, Fawwaz T. Dobson, M. Craig Álvarez-Pérez, José Luis. (2019). *Handbook of Radar Scattering Statistics for Terrain (with Updated Python and MATLAB® Software)*. Artech House. Retrieved from https://app.knovel.com/hotlink/toc/id:kpHRSSTUP2/handbook-radar-scattering/handbook-radar-scattering.
3. Skolnik, Merrill I. (2008). *Radar Handbook, Third Edition*. McGraw-Hill.
4. Cooper, James Arlin. “Comparison of Observed and Calculated Near-Vertical Radar Ground Return Intensities and Fading Spectra.” (1958). Retrieved from https://digitalrepository.unm.edu/ece_etds/378.
5. A. Edison, R. Moore and B. Warner, "Radar terrain return measured at near-vertical incidence," in IRE Transactions on Antennas and Propagation, vol. 8, no. 3, pp. 246-254, May 1960, doi: 10.1109/TAP.1960.1144843.