Radar Systems Engineering
Lecture 14
Airborne Pulse Doppler Radar

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Guest Lecturer

Examples of Airborne Radars

Outline

- Introduction
  - The airborne radar mission and environment
    - Clutter is the main issue
- Different airborne radar missions
  - Pulse Doppler radar in small fighter / interceptor aircraft
    - F-14, F-15, F-16, F-35
  - Airborne, surveillance, early warning radars
    - E-2C (Hawkeye), E-3 (AWACS), E-8A (JOINT STARS)
  - Airborne synthetic aperture radar
    - Military and civilian remote sensing missions
    - To be covered in lecture 19, later in the course
- Summary

Block Diagram of Radar System

[Clutter as seen from an airborne platform](), [Signal waveforms](), and [Doppler processing]() will be the focus in this lecture

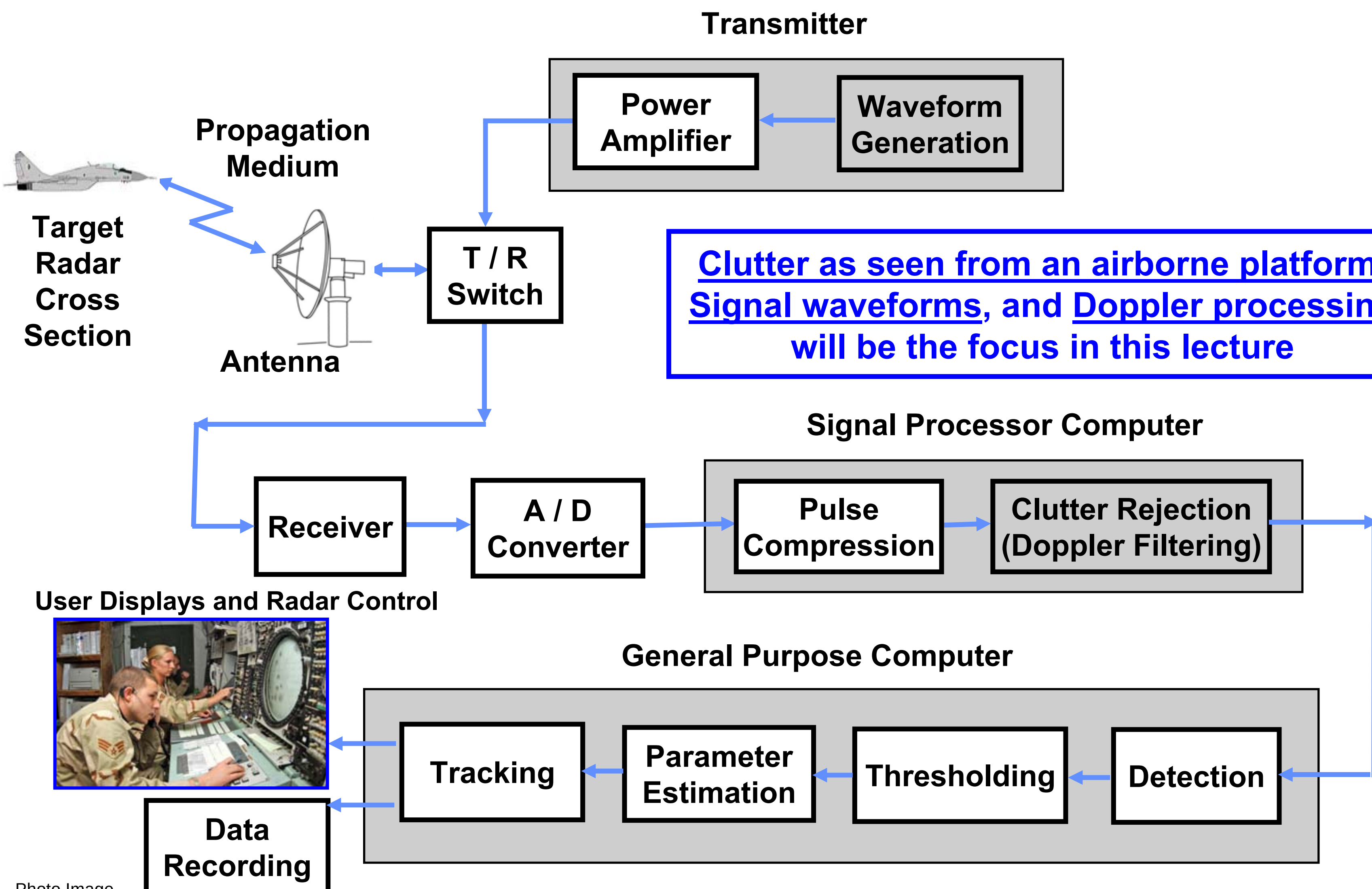
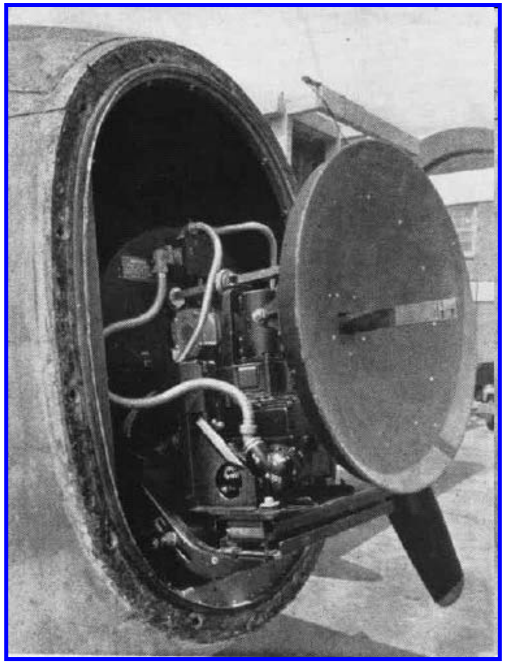


Photo Image
Courtesy of US Air Force

First Use of Airborne Radars

US APS-3 Radar
with Dish Antenna-
3 cm wavelength



Courtesy of US Navy

German "Lichtenstein" Radar
Dipole array – 75 / 90 cm wavelength

Courtesy of Department of Defense

- **When they were introduced on airborne platforms during World War II, they were used to detect hostile aircraft at night in either a defensive or an offensive mode**

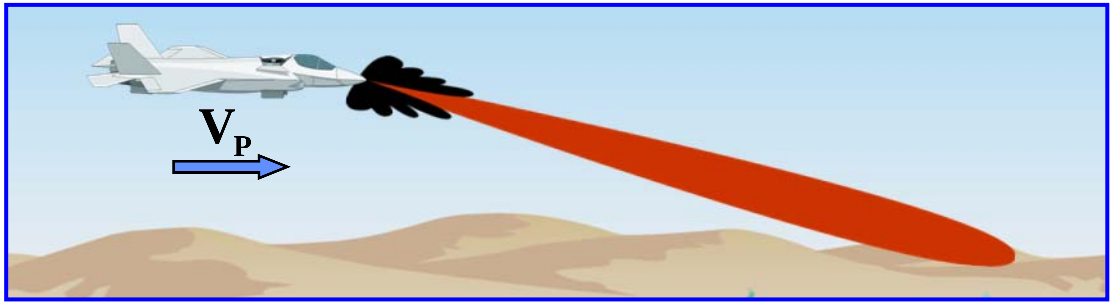
Role of Airborne Military Radars

- **Missions and Functions**
  - Surveillance, Tracking, Fire Control
  - Reconnaissance
  - Intelligence

- **Examples**
  - Air-to-air fighter combat
    - Aircraft interception (against air breathing targets)
  - Airborne Early warning
  - Air to ground missions
  - Close air support
  - Ground target detection and tracking

- **Radar modes**
  - Pulse Doppler radar
  - Synthetic Aperture radar
  - Displaced Phase Center Antenna (DPCA)
  - Ground Moving Target Indication

Geometry of Airborne Clutter



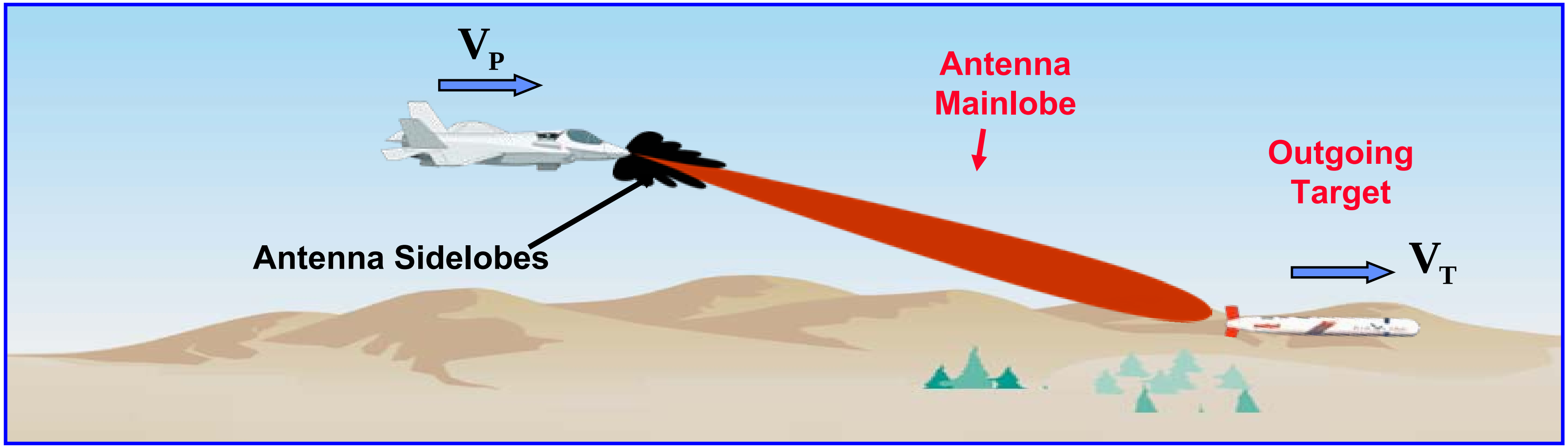
- **Key components of the ground clutter echo from radar's on an airborne platform:**
  - **Main beam of antenna illuminates the ground**
  - **Antenna sidelobes illuminate clutter over a wide range of viewing angles**
  - **Altitude return reflects from the ground directly below the radar**

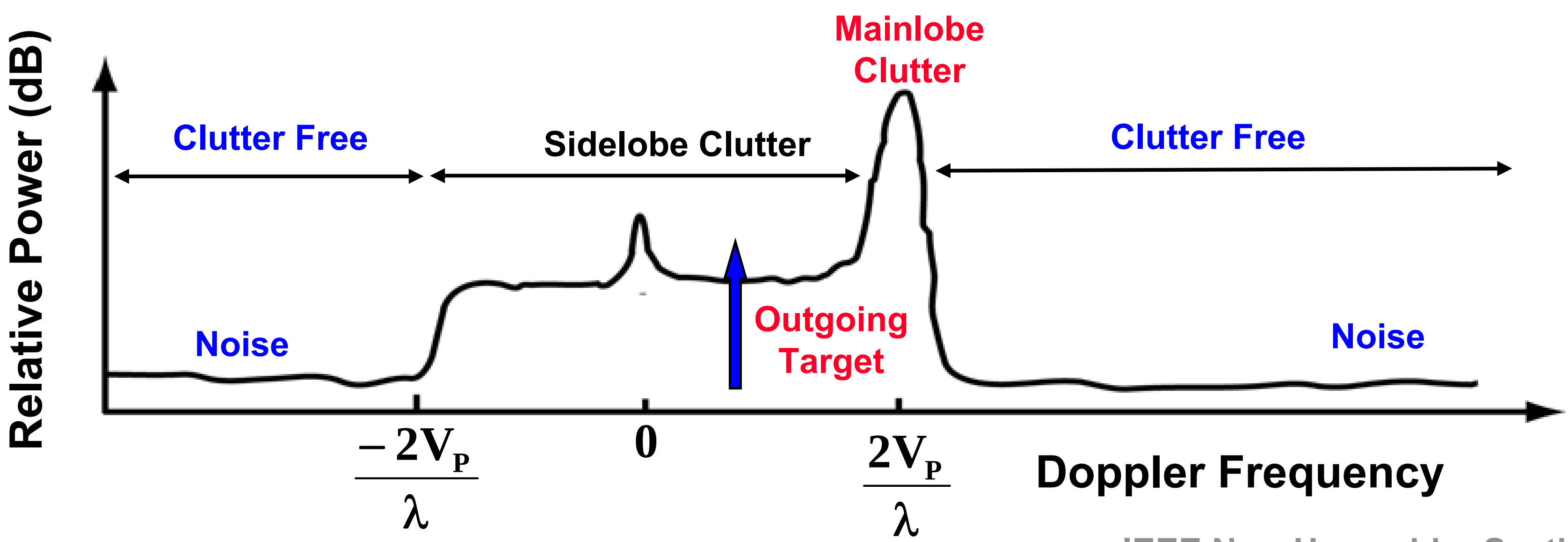
The Doppler frequency distributions of these effects and how they affect radar performance differ with:

1. **radar platform velocity (speed and angle), and**
2. **the geometry (aspect angle of aircraft relative to ground illumination point)**

Airborne Radar Clutter Spectrum

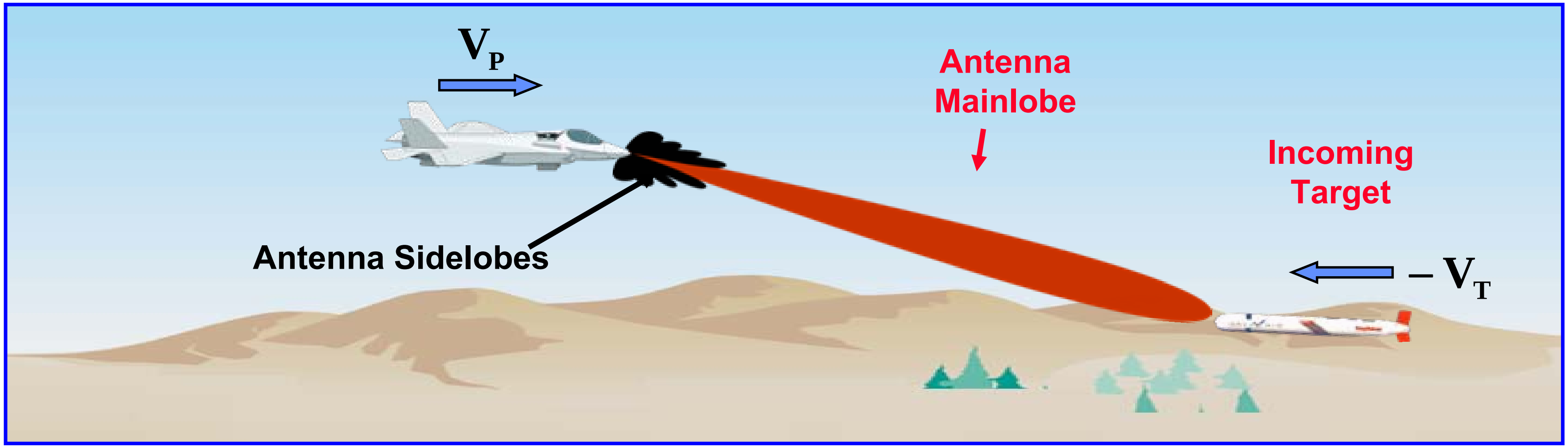
No Doppler Ambiguities V_P **and** V_T **in same vertical plane**

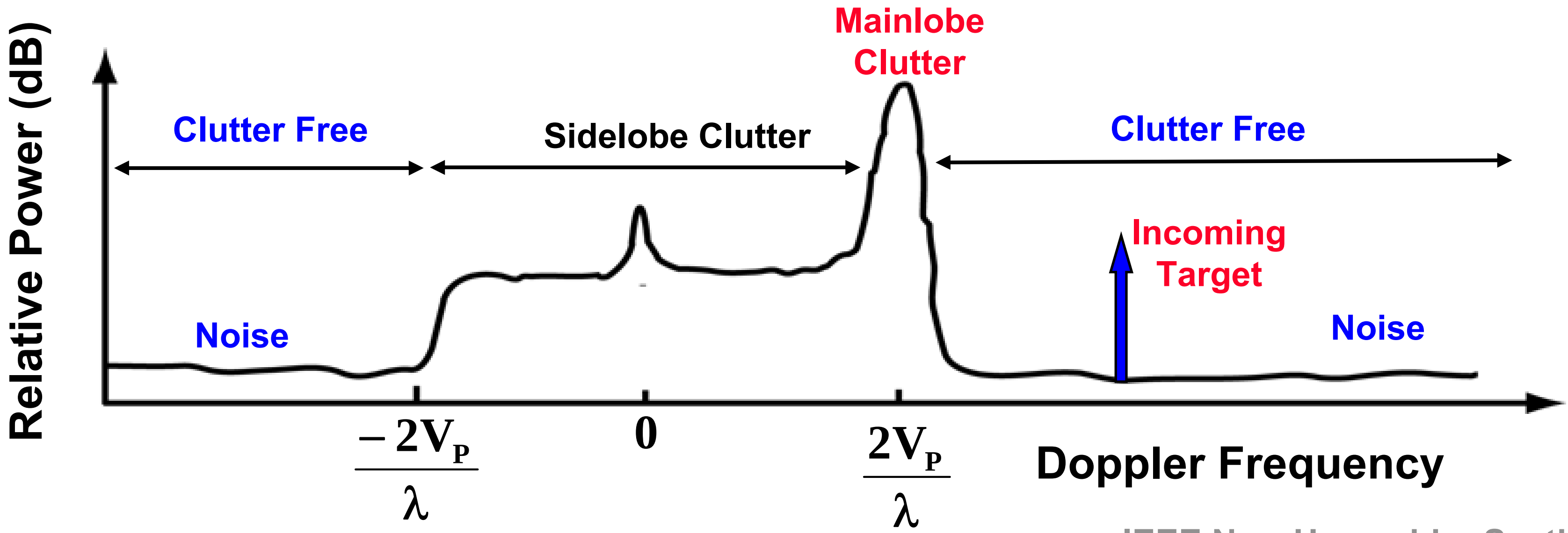




Airborne Radar Clutter Spectrum

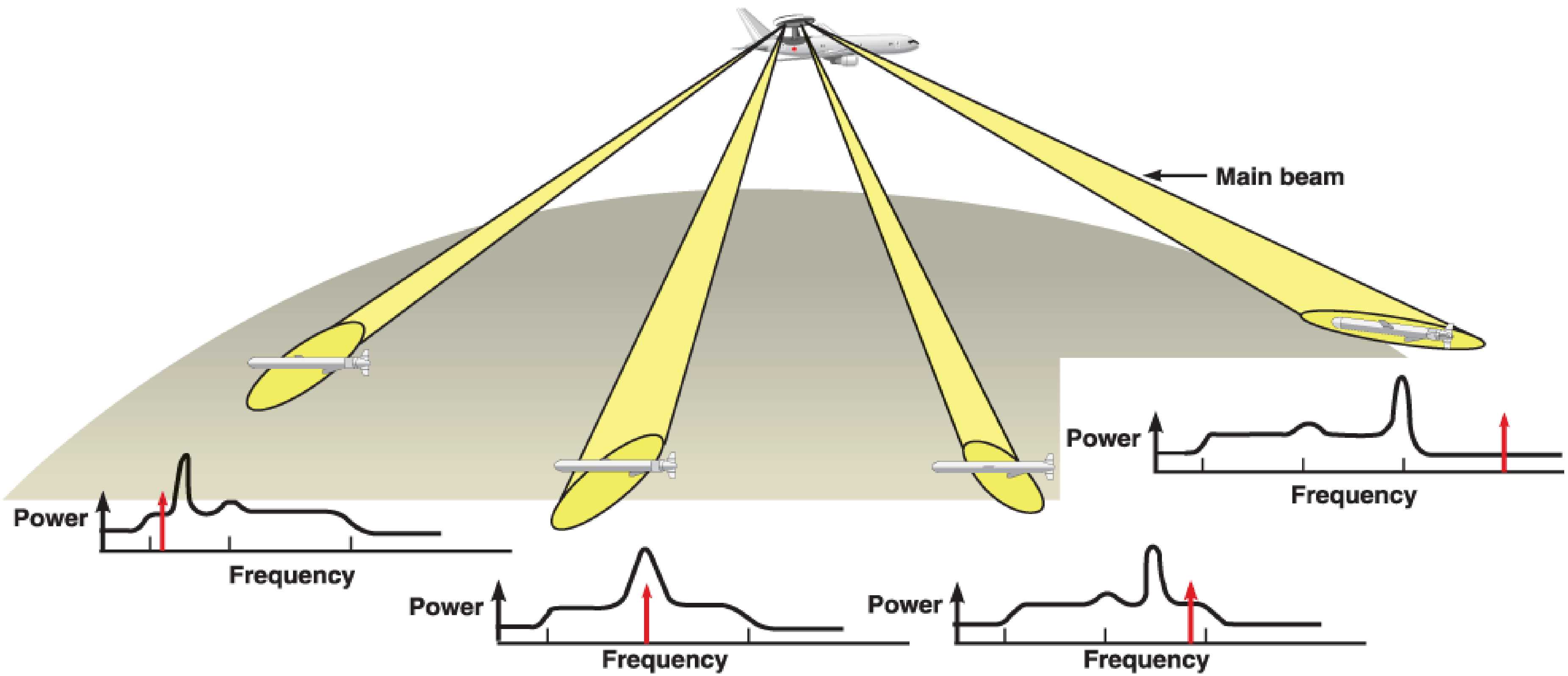
No Doppler Ambiguities V_P **and** V_T **in same vertical plane**





Airborne Radar Clutter Characteristics

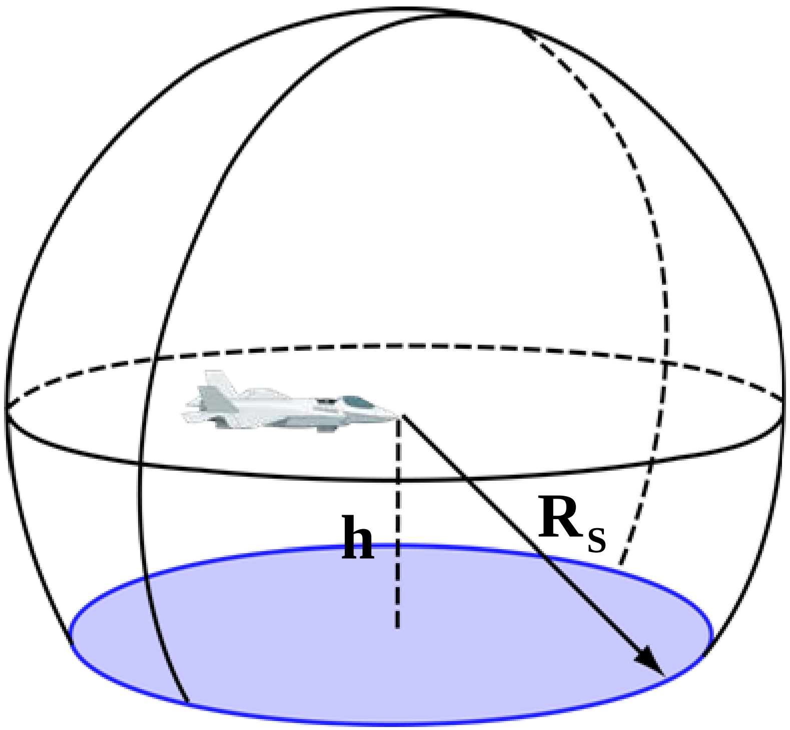
- Illustrative example
- Without Pulse-Doppler ambiguities



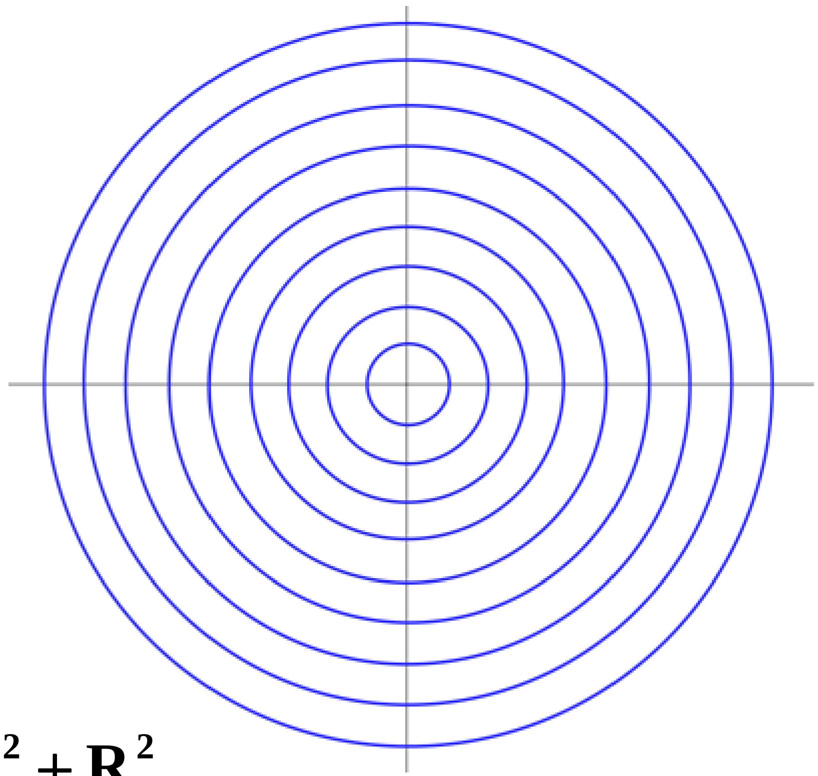
- Doppler frequency of mainbeam clutter depends on scan direction
- Doppler frequency of target depends on scan direction and target aspect angle

Constant Range Contours on the Ground

Range to Ground Scenario



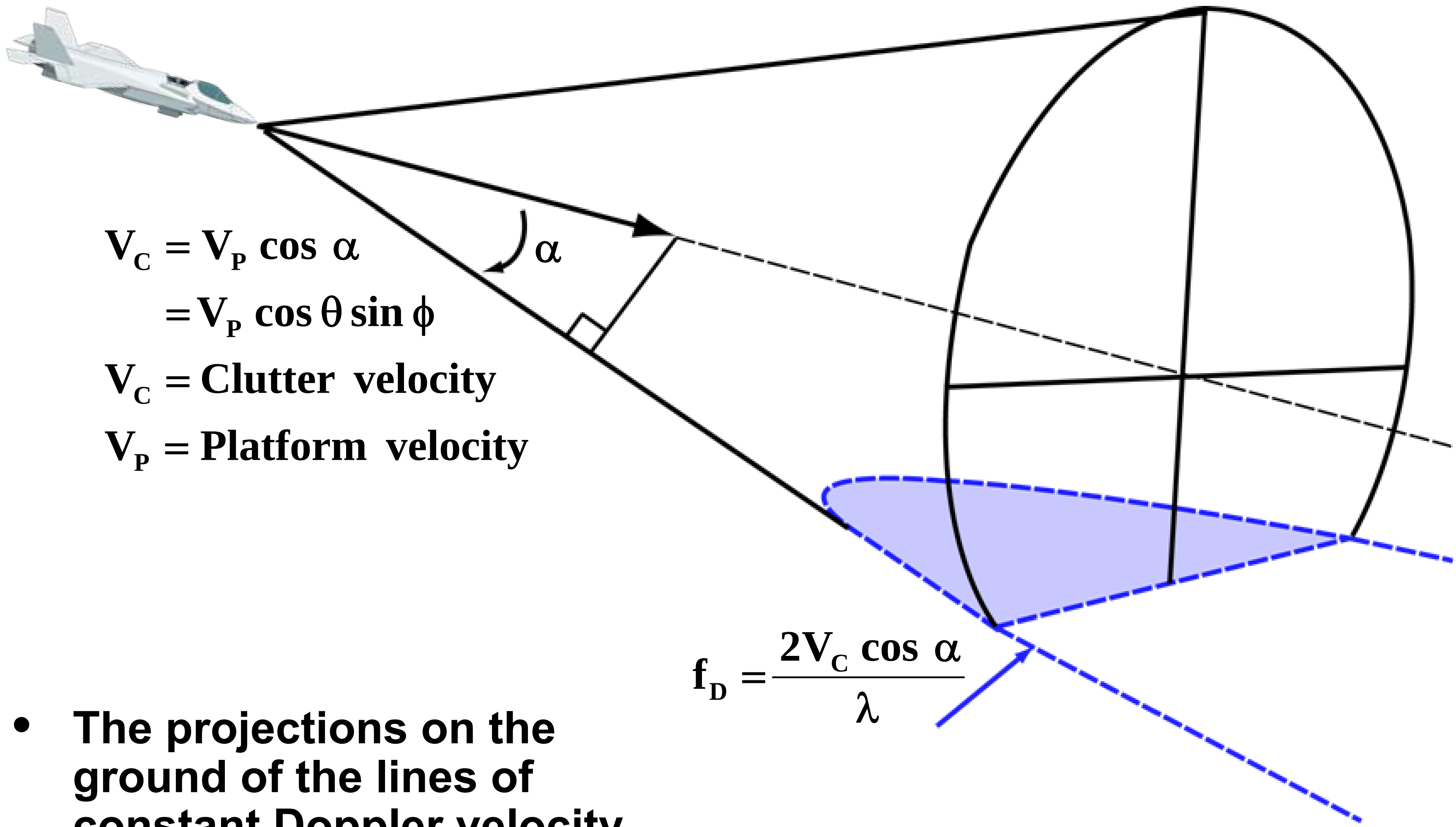
Lines of Constant Range to Ground



$$R_S^2 = h^2 + R_G^2$$

- **The projections on the ground of the lines of constant range are a set circles**

Constant Doppler Velocity Contours on the Ground

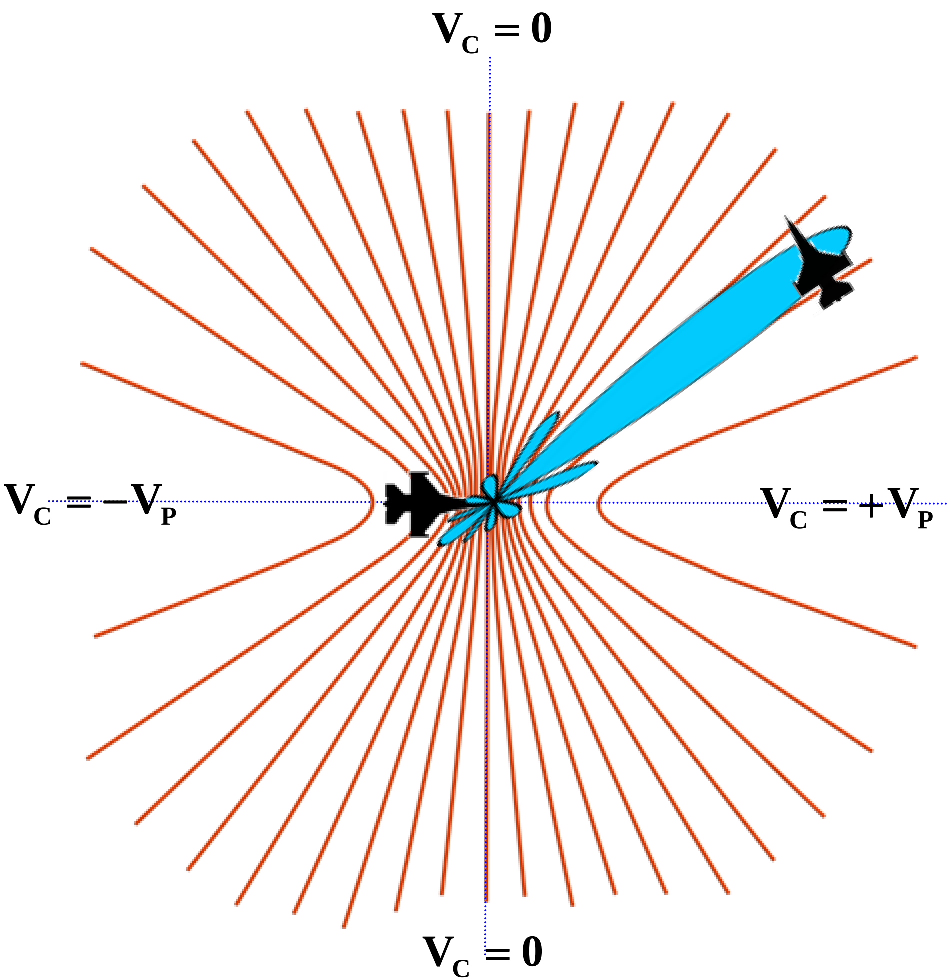


$$V_C = V_P \cos \alpha$$
$$= V_P \cos\theta \sin\phi$$
$$V_C = \text{Clutter velocity}$$
$$V_P = \text{Platform velocity}$$

$$f_D = \frac{2V_C \cos \alpha}{\lambda}$$

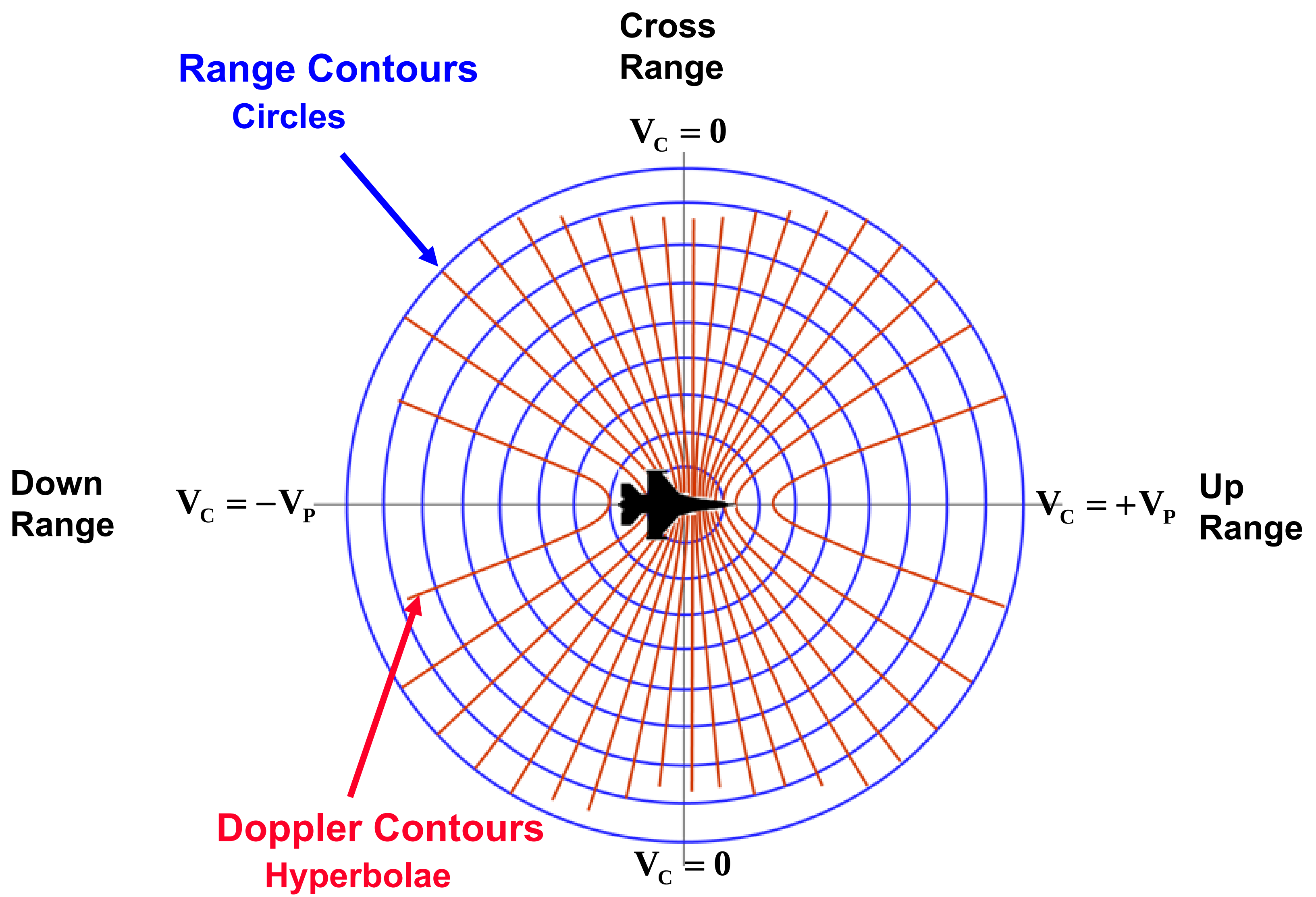
- **The projections on the ground of the lines of constant Doppler velocity are a set hyperbolae**

Constant Doppler Contours on Ground

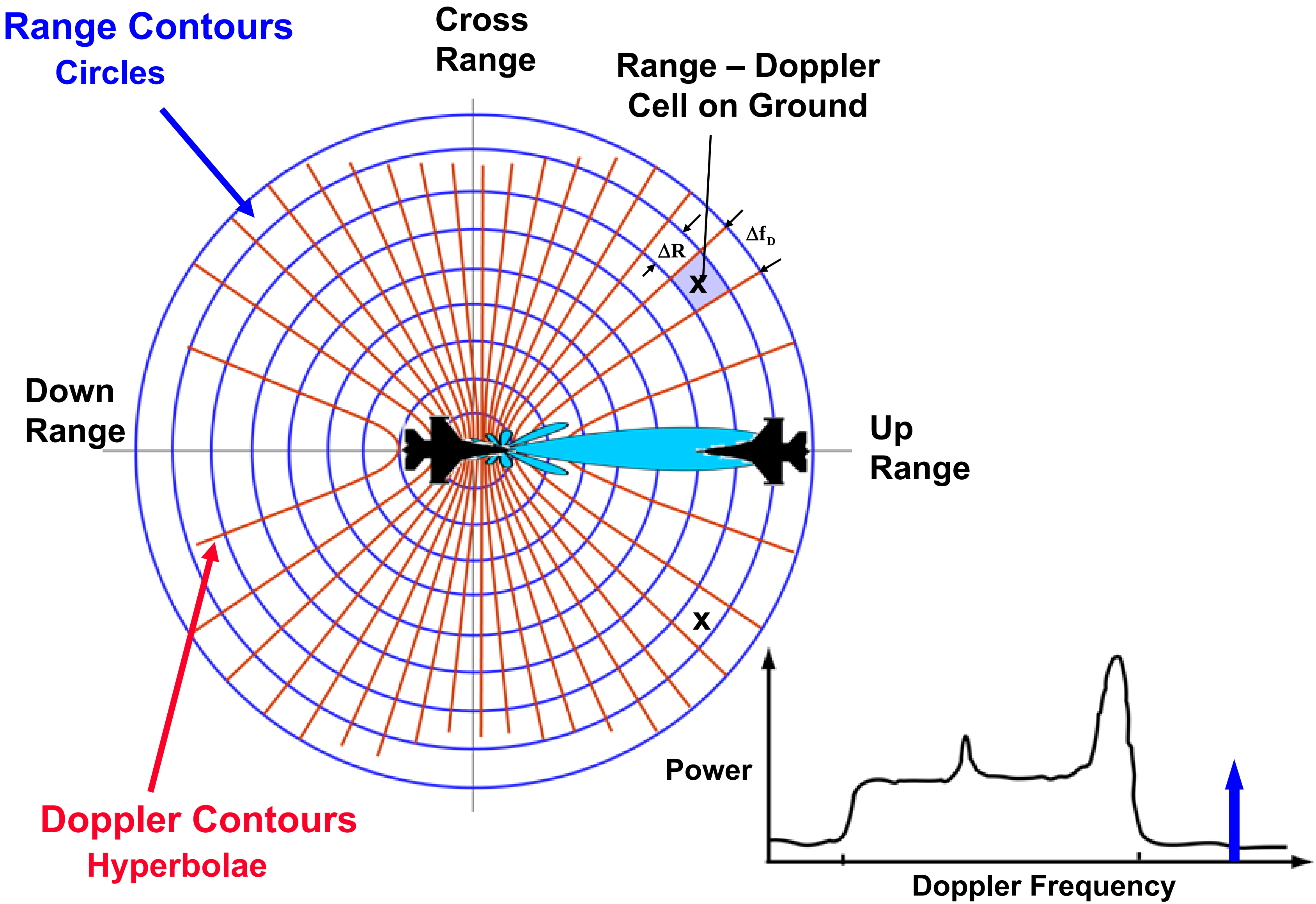


- The lines of constant Doppler frequency/velocity are called “Isodops”
- The equation for the family of hyperbolae depend on:
  - Airborne radar height above ground
  - Angle between airborne radar velocity and the point on the ground that is illuminated
  - Wavelength of radar

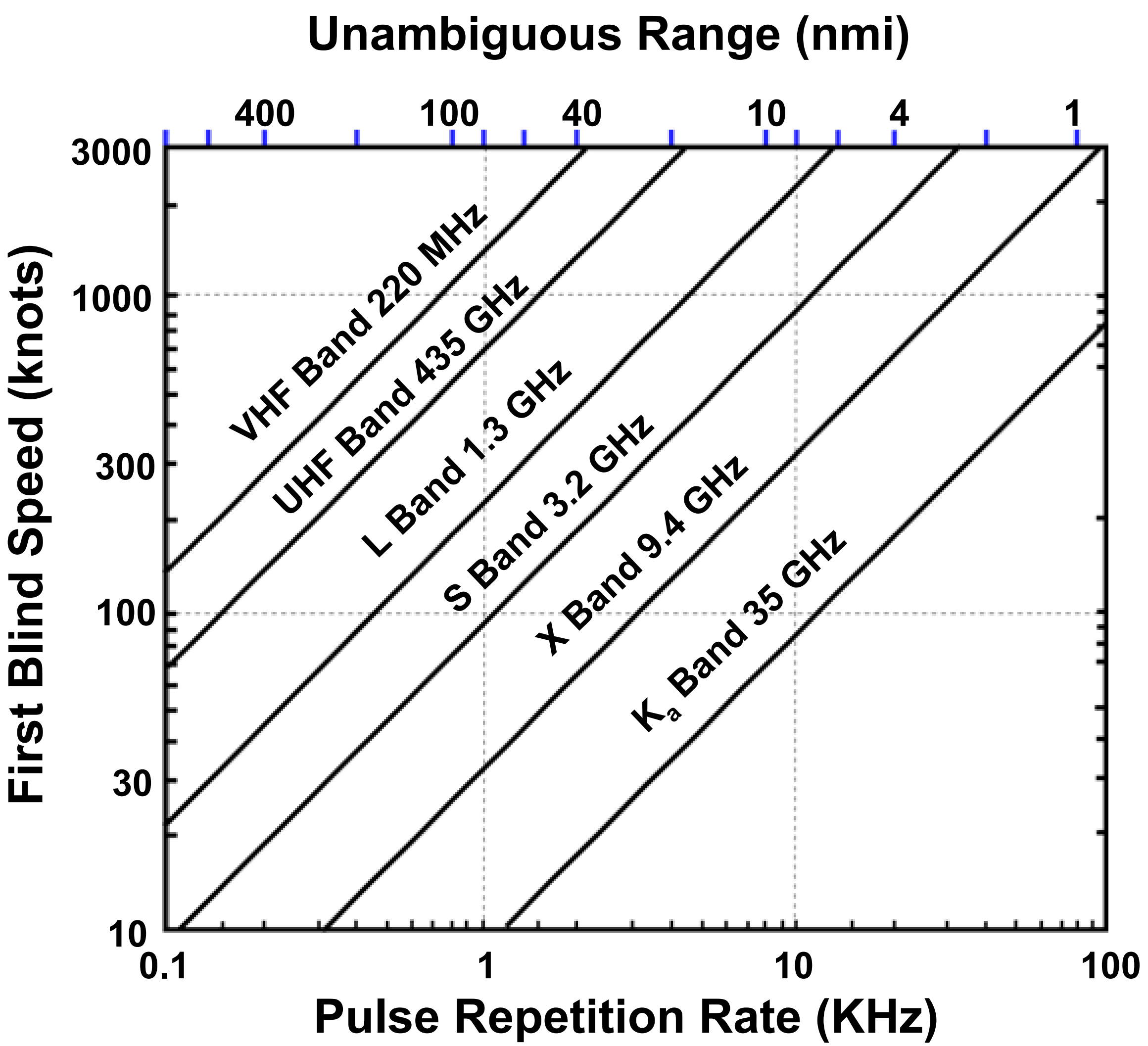
Range-Doppler Ground Clutter Contours



Range-Doppler Ground Clutter Contours



Unambiguous Doppler Velocity and Range



$$V_B = \frac{\lambda f_{PRF}}{2}$$

and

$$R_U = \frac{c}{2 f_{PRF}}$$

Yields

$$V_B = \frac{\lambda c}{4 R_U}$$

Classes of Pulse Doppler Radars

	Range Measurement	Doppler Measurement
Low PRF	Unambiguous	Highly Ambiguous
Medium PRF	Ambiguous	Ambiguous
High PRF	Highly Ambiguous	Unambiguous

Missions for Airborne Military Radars "The Big Picture"

- Fighter / Interceptor Radars
  - Antenna size constraints imply frequencies at X-Band or higher
    - Reasonable angle beamwidths
  - This implies Medium or High PRF pulse Doppler modes for look down capability
- Wide Area Surveillance and Tracking
  - Pulse Doppler solutions
    - Low, Medium and/or High PRFs may be used depending on the specific mission
  - E-2C UHF
  - AWACS S-Band
  - Joint Stars X-Band
- Synthetic Aperture Radars will be discussed in a later lecture

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    - F-14, F-15, F-16, F-35
      - High PRF Modes
      - Medium PRF Modes
  - Airborne, surveillance, early warning radars
    - E-2C (Hawkeye), E-3 (AWACS), E-8A (JOINT STARS)
  - Airborne synthetic aperture radar
    - Military and civilian remote sensing missions
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Photographs of Fighter Radars

APG-65 (F-18)


Courtesy of Raytheon
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Courtesy of Northrop Grumman
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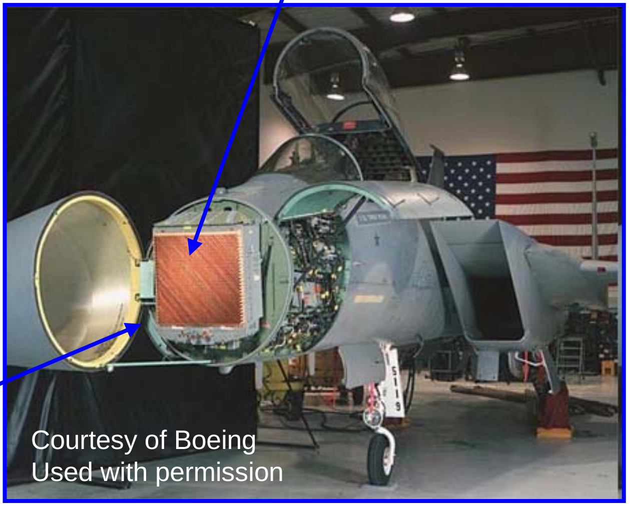
APG-66 (F-16)

Active Electronically Scanned Arrays (AESA)

APG-63 V(2) (F-15C)


Courtesy of Boeing
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Radar built by Raytheon


Courtesy of Northrop Grumman
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Courtesy of USAF

APG-81 (F-35)

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Pulse Doppler PRFs

Frequency	PRF Type	PRF Range*	Duty Cycle*
• X- Band	High PRF	100 - 300 KHz	< 50%
• X- Band	Medium PRF	10 - 30 KHz	~ 5%
• X- Band	Low PRF	1 - 3 KHz	~.5%
• UHF	Low PRF	300 Hz	Low

* Typical values only; specific radars may vary inside and outside these limits

High PRF Mode

Frequency	PRF Type	PRF Range*	Duty Cycle*
X- Band	High PRF	100 - 300 KHz	< 50%

Example: PRF = 150 KHz Duty Cycle = 35%

PRI= 6.67 μsec Pulsewidth = 2.33 μsec

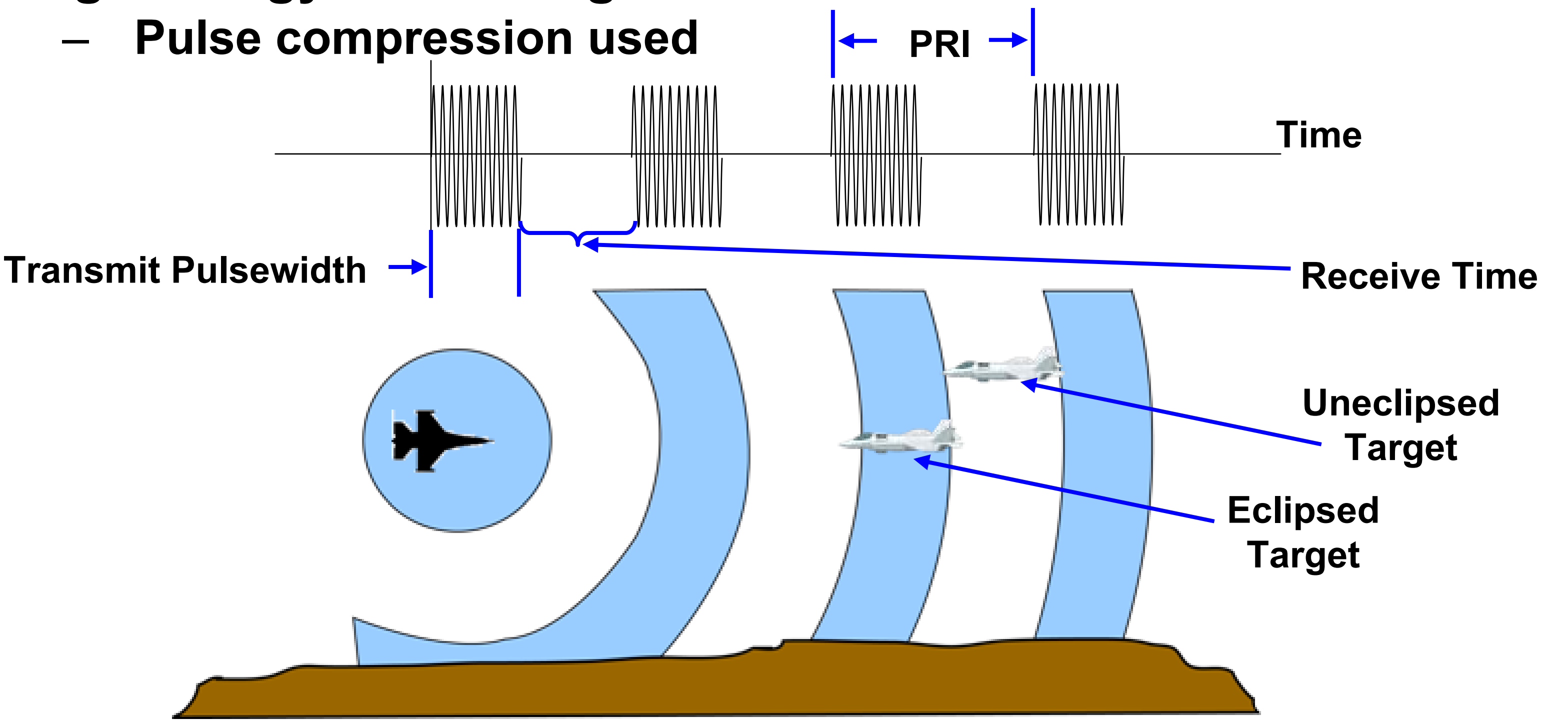
Unambiguous Range = 1 km

Unambiguous Doppler Velocity = 4,500 knots

- For high PRF mode :
  - Range – Highly ambiguous
    - Range ambiguities resolved using techniques discussed in Lecture 13
  - Doppler velocity – Unambiguous
    - For nose on encounters, detection is clutter free
  - High duty cycle implies significant “Eclipsing Loss”
    - Multiple PRFs, or other techniques required

High PRF Mode – Range Eclipsing

- High PRF airborne radars tend to have a **High Duty** cycle to get high energy on the target
  - Pulse compression used



- Eclipsing loss is caused because the receiver cannot be receiving target echoes when the radar is transmitting
  - Can be significant for high duty cycle radars
  - Loss can easily be 1-2 dB, if not mitigated

High PRF Pulse Doppler Radar

- No Doppler velocity ambiguities, many range ambiguities
  - Significant range eclipsing loss
- Range ambiguities can be resolved by transmitting 3 redundant waveforms, each at a different PRF
  - Often only a single range gate is employed, but with a large Doppler filter bank
- The antenna side lobes must be very low to minimize sidelobe clutter
  - Short range sidelobe clutter often masks low radial velocity targets
- High closing speed aircraft are detected at long range in clutter free region
- Range accuracy and ability to resolve multiple targets can be poorer than with other waveforms

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Medium PRF Mode

Frequency	PRF Type	PRF Range*	Duty Cycle*
• X- Band	Medium PRF	10 - 30 KHz	~ 5%

Example : 7 PRF = 5.75, 6.5, 7.25, 8, 8.75, 9.5 & 10.25 KHz

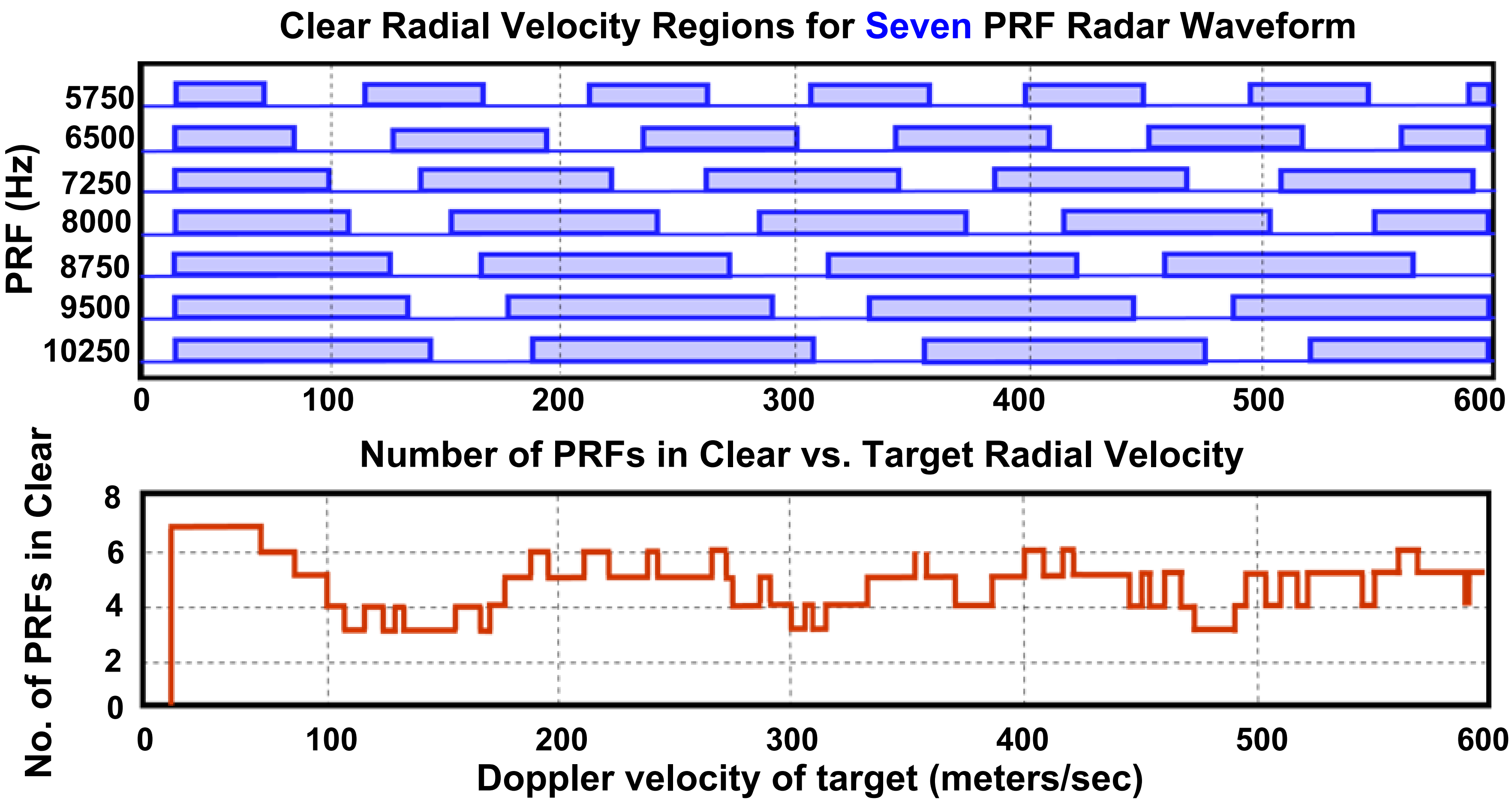
(From Figure 3.44 in text)

Range Ambiguities = ~14 to 26 km

Blind Speeds = ~175 to 310 knots

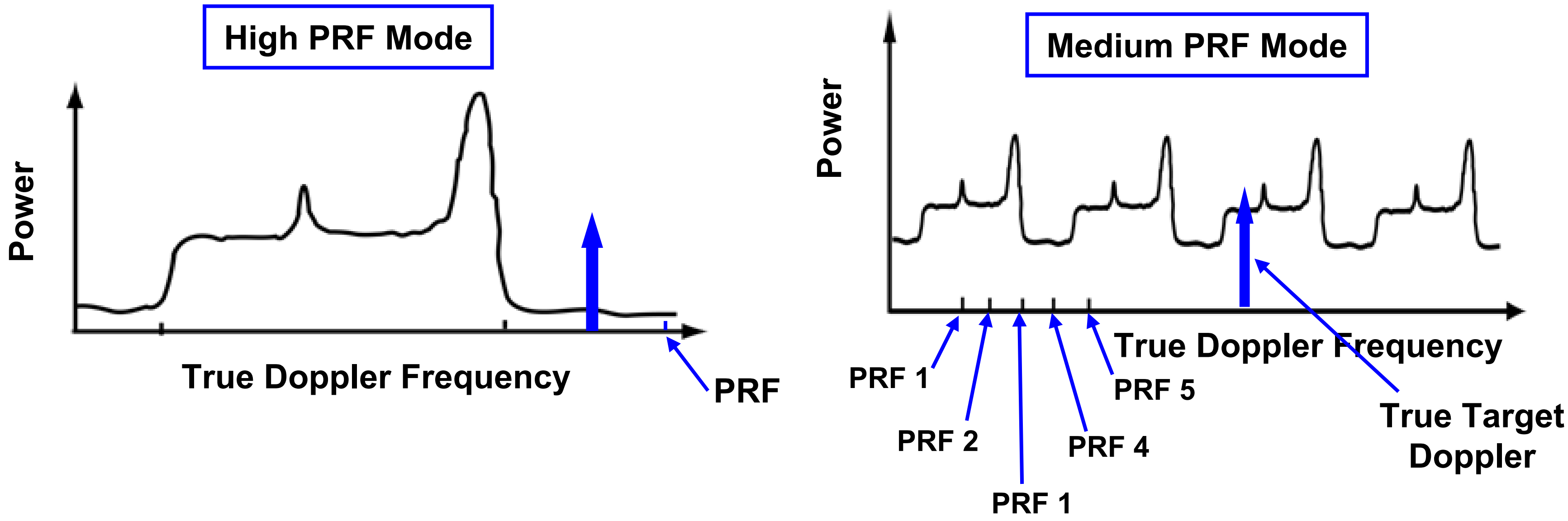
- For the medium PRF mode :
  - Clutter and target ambiguities in range and velocity
  - Clutter from antenna sidelobes is an significant issue

Clear Velocity Regions for a Medium PRF Radar



- **The multiple PRFs (typically 7) and their associated higher radar power are required to obtain sufficient detections to unravel range and velocity ambiguities in medium PRF radars**

Medium PRF Mode



- In the Doppler domain, the target and clutter alias (fold down) into the range 0 to PRF1, PRF2, etc.
  - Because of the aliasing of sidelobe clutter, medium PRF radars should have very low sidelobes to mitigate this problem
- In the range domain similar aliasing occurs
  - Sensitivity Time Control (STC) cannot be used to reduce clutter effects (noted in earlier lectures)
- Range and Doppler ambiguity resolution techniques described in previous lecture

Medium PRF Pulse Doppler Radar

- Both range and Doppler ambiguities exist
  - Seven or eight different PRFs must be used
  - Insures target seen at enough Doppler frequencies to resolve range ambiguities
  - Transmitter larger because of redundant waveforms used to resolve ambiguities

- There is no clutter free region
  - Fewer range ambiguities implies less of a problem with sidelobe clutter
  - Antenna must have low sidelobes to reduce sidelobe clutter

- Often best single waveform for airborne fighter / interceptor

- More range gates than high PRF, but fewer Doppler filters for each range gate

- Better range accuracy and Doppler resolution than high PRF systems

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Airborne Surveillance & Tracking Radars

- **Missions and Functions**
  - Surveillance, Tracking, Fire Control
  - Reconnaissance
  - Intelligence

- **Examples**
  - Airborne early warning
  - Ground target detection and tracking

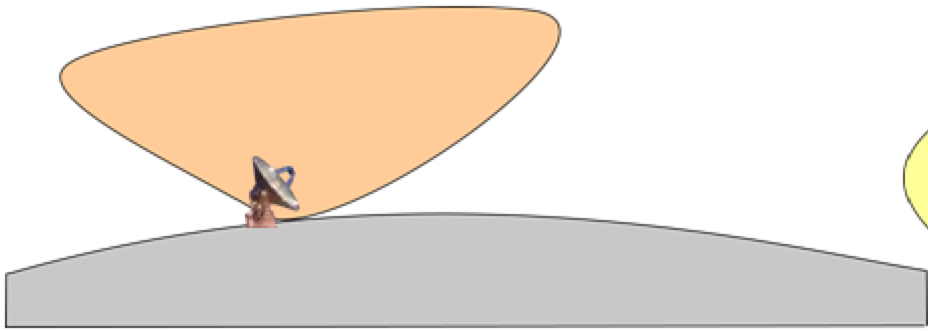
- **Radar modes**
  - Pulse Doppler radar
  - Synthetic Aperture radar
  - Displaced Phase Center Antenna (DPCA)
  - Other modes/techniques

Elevated radar platforms provide long range and over the horizon coverage of airborne and ground based targets

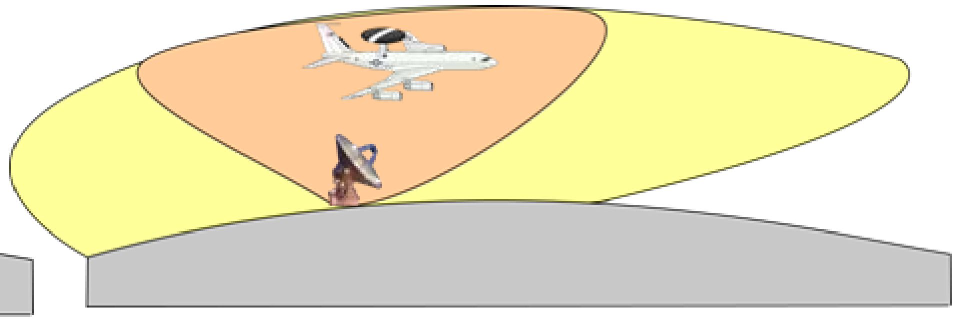
Examples of Airborne Radars

AEW Radar Coverage

Ground Based Surveillance Radar Coverage

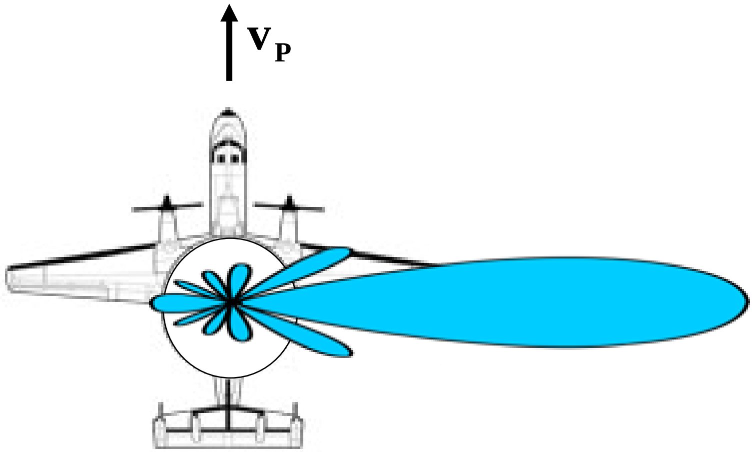


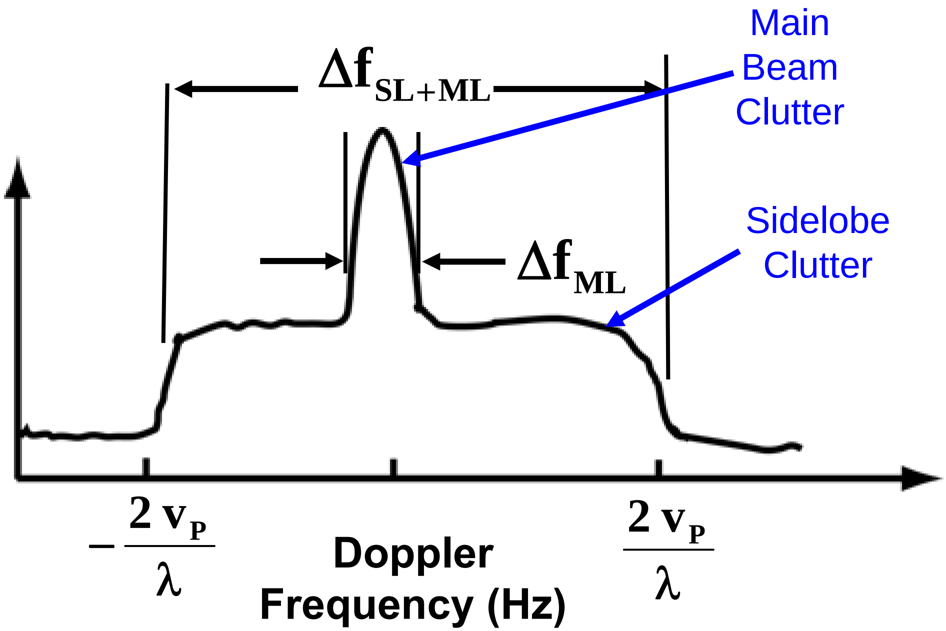
Airborne Surveillance Radar Coverage



- **Elevating the radar can extend radar coverage well out over the horizon**
- **Range Coverage -400 km to 800 km**
  - Ground based radars ~400 km
  - Airborne radar ~800 km
- **Issues**
  - High acquisition and operating costs
  - Limited Antenna size
  - Radar Weight and prime power
  - More challenging clutter environment

Characteristics of Ground Clutter (from Airborne Platform)





Ground Clutter Doppler Frequency

$$f_C = \frac{2\,v_P}{\lambda}\cos\,\alpha = \frac{2\,v_P}{\lambda}\cos\,\theta\sin\phi$$

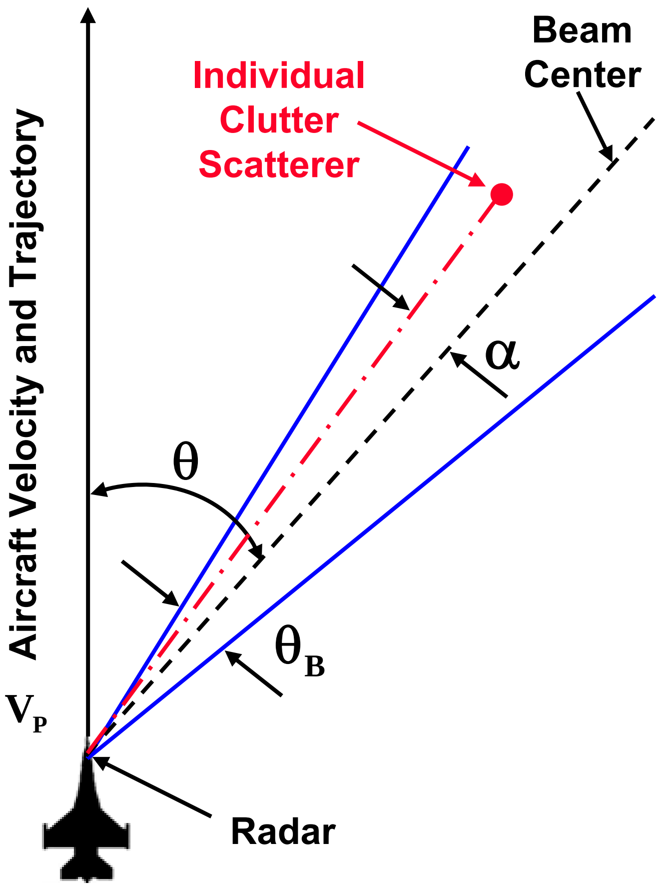
Doppler Frequency Width (Sidelobe + Main Beam Clutter)

$$\Delta f_{SL+ML} = \frac{4\,v_P}{\lambda}$$

Doppler Frequency Width of Main Beam Clutter (Null to Null)

$$\Delta f_{MB} = \frac{4\,v_P}{\lambda}\frac{\lambda}{L} = \frac{4\,v_P}{L}$$

Spread of Main Beam Clutter



Spread of Main Beam Clutter Maximum at θ = 90°

Adapted from Skolnik Reference 1

Depression angle of beam neglected

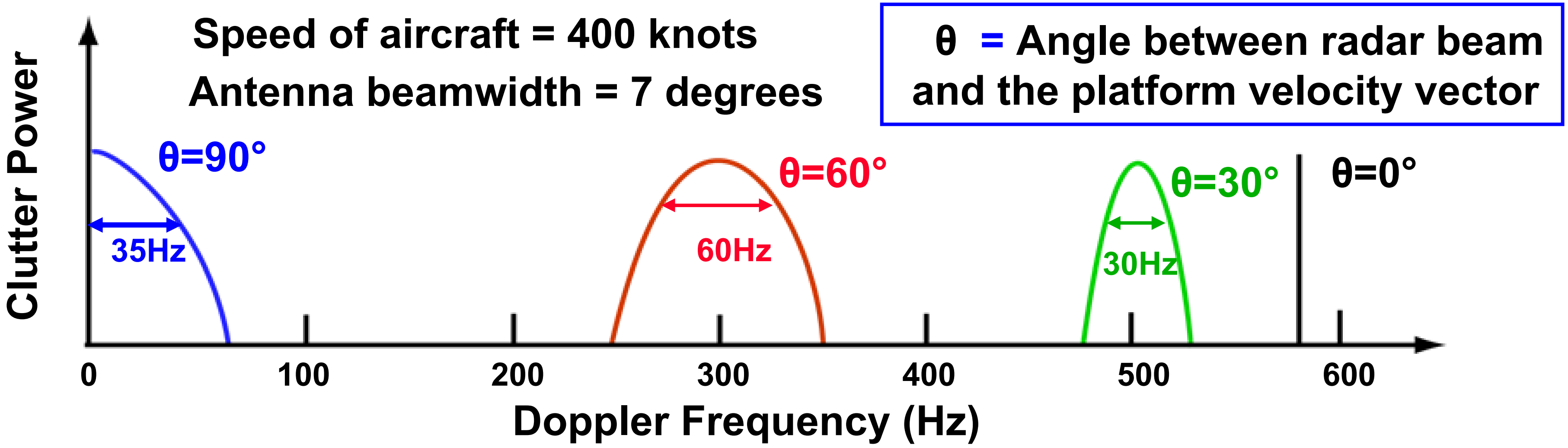
- **Doppler frequency of clutter return depends on angle of clutter with velocity vector of aircraft**
- **Doppler frequency of clutter return at center of beam**

$$f_C = \frac{2\,V_P}{\lambda} \cos\theta$$

- **Doppler spread of main beam clutter can be found by differentiating this equation**

$$\Delta f_C = \frac{2\,V_P}{\lambda}\,\theta_B \sin\theta$$

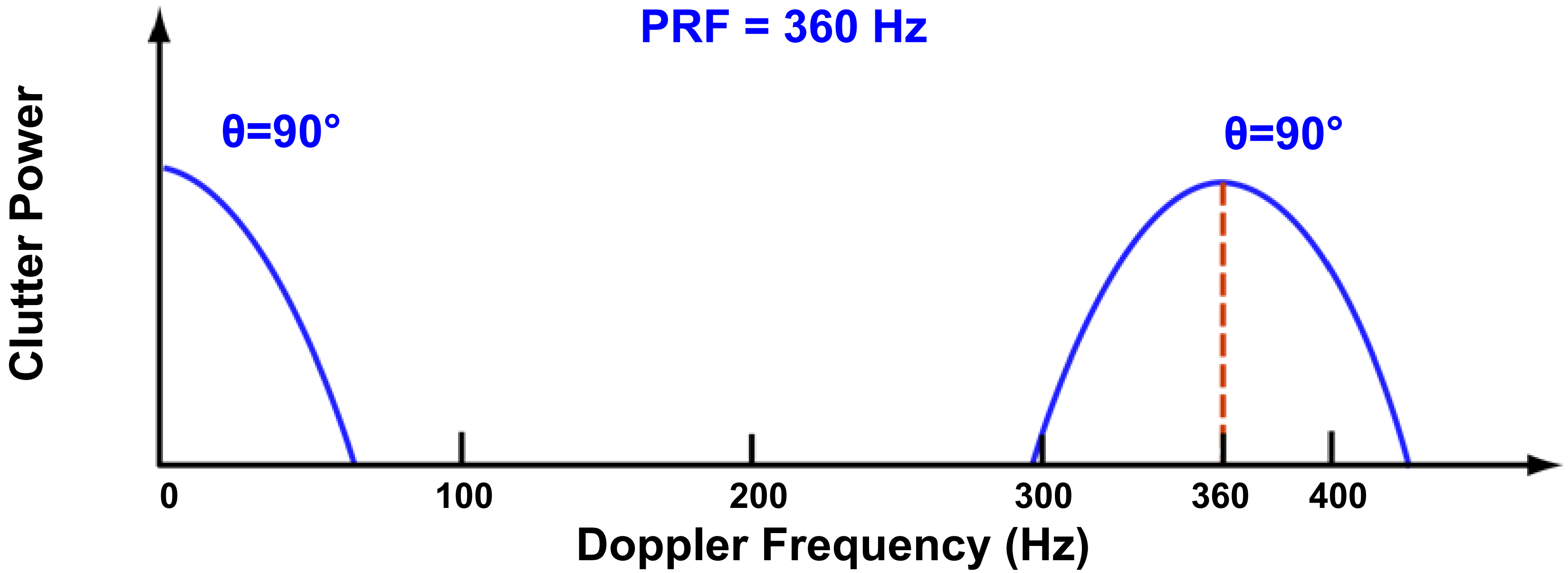
Clutter Spread with a UHF Airborne Radar



- Both the width of the clutter spectra and its center frequency depend on the angle θ
- When the antenna points in the direction of the platform velocity vector, the Doppler shift of the clutter echo is maximum, but the width of the spectrum is theoretically zero
- When the antenna is directed in the direction perpendicular to the direction of the platform velocity, the clutter center frequency is zero, but the spread is maximum

Adapted from Skolnik Reference 1

Aliasing of Clutter in Low PRF UHF Airborne Radar



- PRF = 360 Hz corresponds to a maximum unambiguous range of 225 nmi
- A relatively large portion of the frequency domain (Doppler space) is occupied by the clutter spectrum because of platform motion
- The widening of the clutter needs to be reduced in order for standard clutter suppression techniques to be effective

AEW Airborne Radar Clutter Rejection

- There are 2 effects that can seriously degrade the performance of a radar on a moving platform
  - A non-zero Doppler clutter shift
  - A widening of the clutter spectrum
- These may be compensated for by two different techniques
  - TACCAR (Time Averaged Clutter Coherent Airborne Radar)
    - The change in center frequency of the clutter spectrum
  - DPCA (Displaced Phase Center Antenna)
    - The widening of the clutter spectrum
- Radars which have used these techniques, over the years, to compensate for platform motion are Airborne Early Warning radars

Compensation for Clutter Doppler Shift

- TACCAR (Time Averaged Clutter Coherent Airborne Radar)
  - Also called "Clutter Lock MTI"

- The Doppler frequency shift from ground clutter can be compensated by using the clutter echo signal itself to set the frequency of the reference oscillator (or coho)
  - This process centers the ground clutter to zero Doppler frequency
  - The standard MTI filter (notch at zero Doppler) attenuates the ground clutter

- This technique has been used in ground based radars to mitigate the effect of moving clutter
  - Not used after the advent of Doppler filter processing

AEW Advances - E-2D and MP-RTIP

E-2D

Courtesy of US Navy

MP-RTIP mounted on Proteus Aircraft

Courtesy of US Air Force

- E-2D
  - Mechanically Rotating Active Electronically Scanned Antenna (AESA)
  - Space Time Adaptive Processing (STAP)
- MP-RTIP
  - "Multi-Platform Radar Technology Insertion Program"
  - Originally Joint Stars Upgrade Program
    - Global Hawk and then a wide area surveillance aircraft
  - Advanced ground target surveillance capability

E-3A Sentry - AWACS

Courtesy of USAF

Radar APY-2

S-Band (10 cm wavelength)

Range >250 miles

High PRF waveform to reject clutter in look down mode

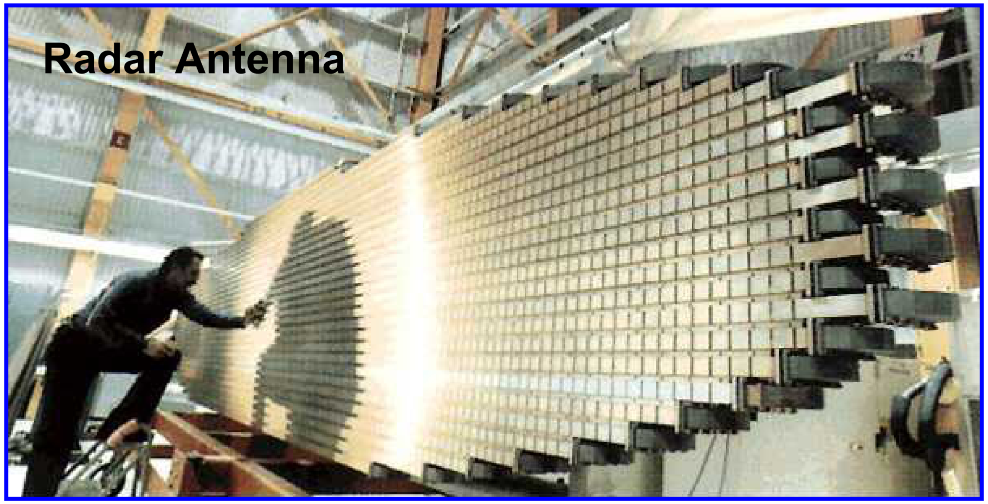
Long range beyond the horizon surveillance mode

Maritime surveillance mode

- AWACS Radar (S-Band)
  - Mission –Long range Surveillance, Command and Control for air tactical environment
  - Radar System Improvement Program (RSIP)
    - Advanced pulse Doppler waveforms
    - Pulse compression added
    - Detection range doubled (over original radar)

See reference 1

AWACS Radar Antenna



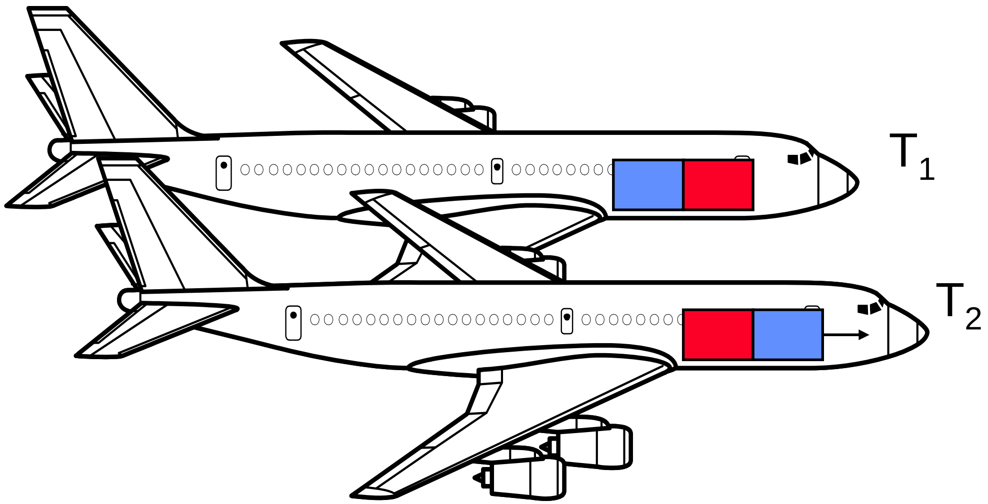
Courtesy of Northrop Grumman
Used with Permission

Radome Diameter 30 ft

- **AWACS (APY-1/2) Antenna**
  - **Phased array – 26 ft by 4.5 ft ultralow sidelobe array**
    Elliptically shaped
  - **28 slotted waveguides with a total of over 4000 slots**
  - **Antenna is mechanically scanned 360° in azimuth**
  - **Uses 28 ferrite reciprocal phase shifters to scan in elevation**
  - **10 sec rotation (data) rate**

See Skolnik reference 1

Displaced Phase Center Antenna (DPCA) Concept



If the aircraft motion is exactly compensated by the movement of the phase center of the antenna beam, then there will be no clutter spread due to aircraft motion, and the clutter can be cancelled with a two pulse canceller

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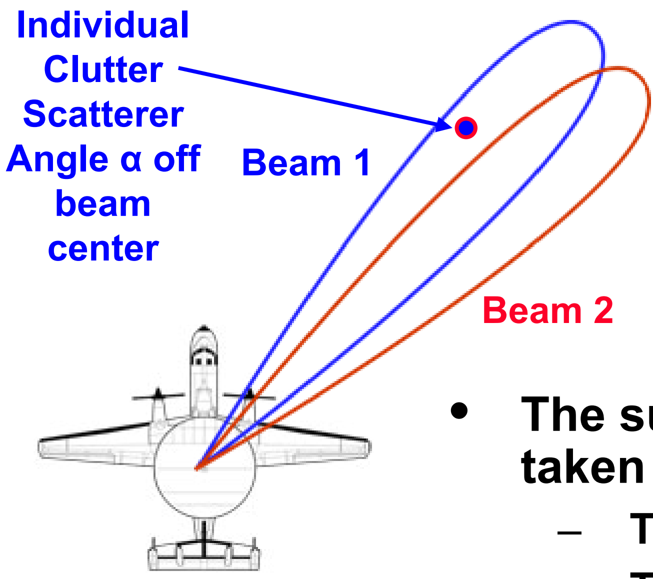
Viewgraph Courtesy of MIT Lincoln Laboratory Used with permission

DPCA for Mechanically Scanned AEW Radar



A mechanically rotating antenna on a moving platform that generates two overlapping (squinted) beams can act as a DCPA when the outputs of the two squinted beams are properly combined

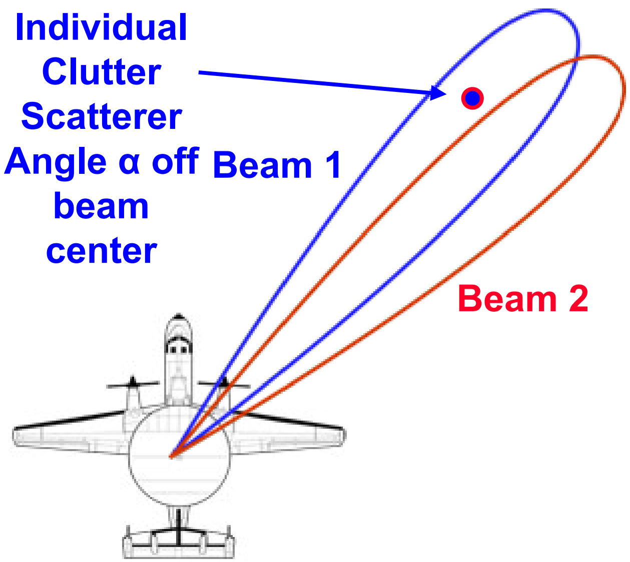
- The sum and difference of the two squinted beams are taken
  - The sum is used for transmit
  - The sum and difference are used on receive

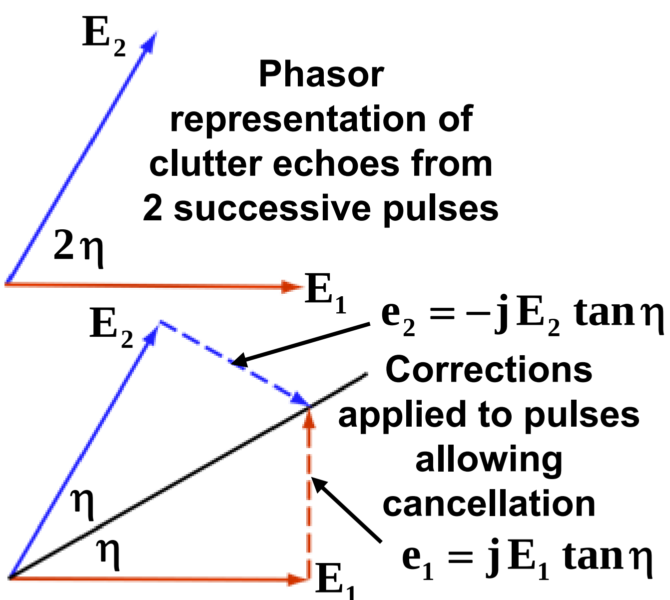
- A phase advance is added to the first pulse and a phase lag is added to the second pulse beams are taken

- The added (or subtracted) phase shift depends on aircraft velocity, the PRF, and the scan angle of the radar relative to the aircraft direction

- The two signals are then subtracted, resulting in the cancellation of the Doppler spread of the clutter

DPCA – The Math- Abbreviated





Σ_R = Sum (2 pulses) of receive signal

Δ_R = Difference (2 pulses) of receive signal

The sum and difference of the two squinted beams are taken

- The sum is used for transmit
- The sum and difference are used on receive

After MUCH manipulation, the corrected received pulses become:

Pulse 1

$$\Sigma_R(\alpha) + jk(v \sin\theta)\Delta_R(\alpha)$$

Pulse 2

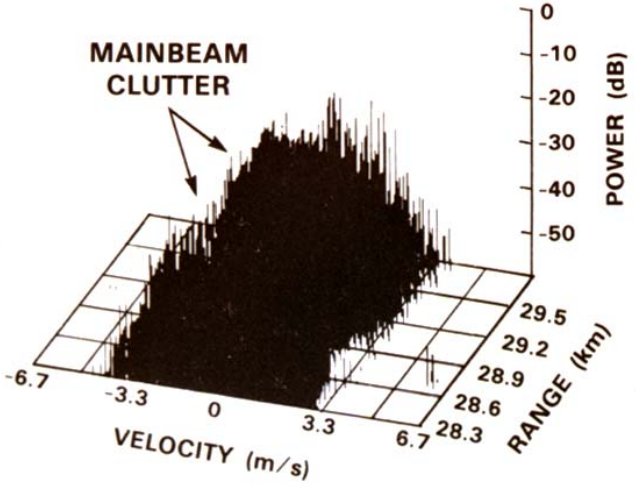
$$\Sigma_R(\alpha) - jk(v \sin\theta)\Delta_R(\alpha)$$

Constant k accounts for differences in Σ and Δ patterns, as well as a factor $4T_P / D$

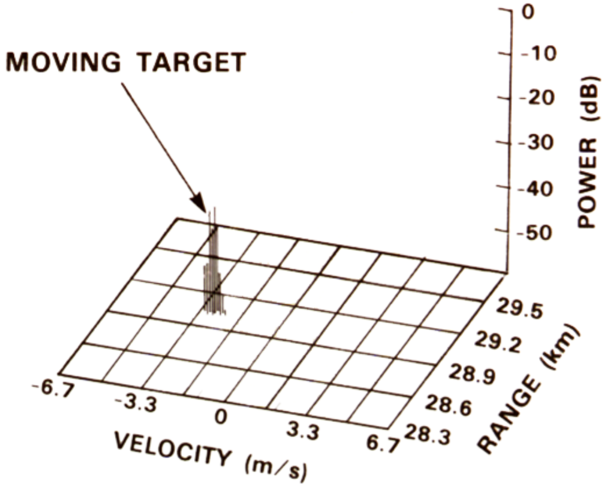
For more detail see Skolnik, Reference 1, pp 166-168

Multiple Antenna Surveillance Radar (MASR)

DPCA Off



DPCA On



Viewgraph Courtesy of MIT Lincoln Laboratory
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Joint Surveillance Target Attack Radar System (Joint STARS)

Courtesy of US Air Force

- **Employs Interferometric SAR for airborne detection of ground vehicles and imaging of ground and surface targets**
  - **Employs APY-3, X Band radar**
- **Mission in wide area surveillance mode:**
  - **Coverage ~50,000 km^2**
  - **Detect, locate, identify, classify, and track trucks, tanks, and other vehicles**
    - **Can differentiate tracked and wheeled vehicles**
    - **Can see vehicles at ranges >200 km , moving at walking speeds**

Joint Stars Radar

JSTARS Antenna

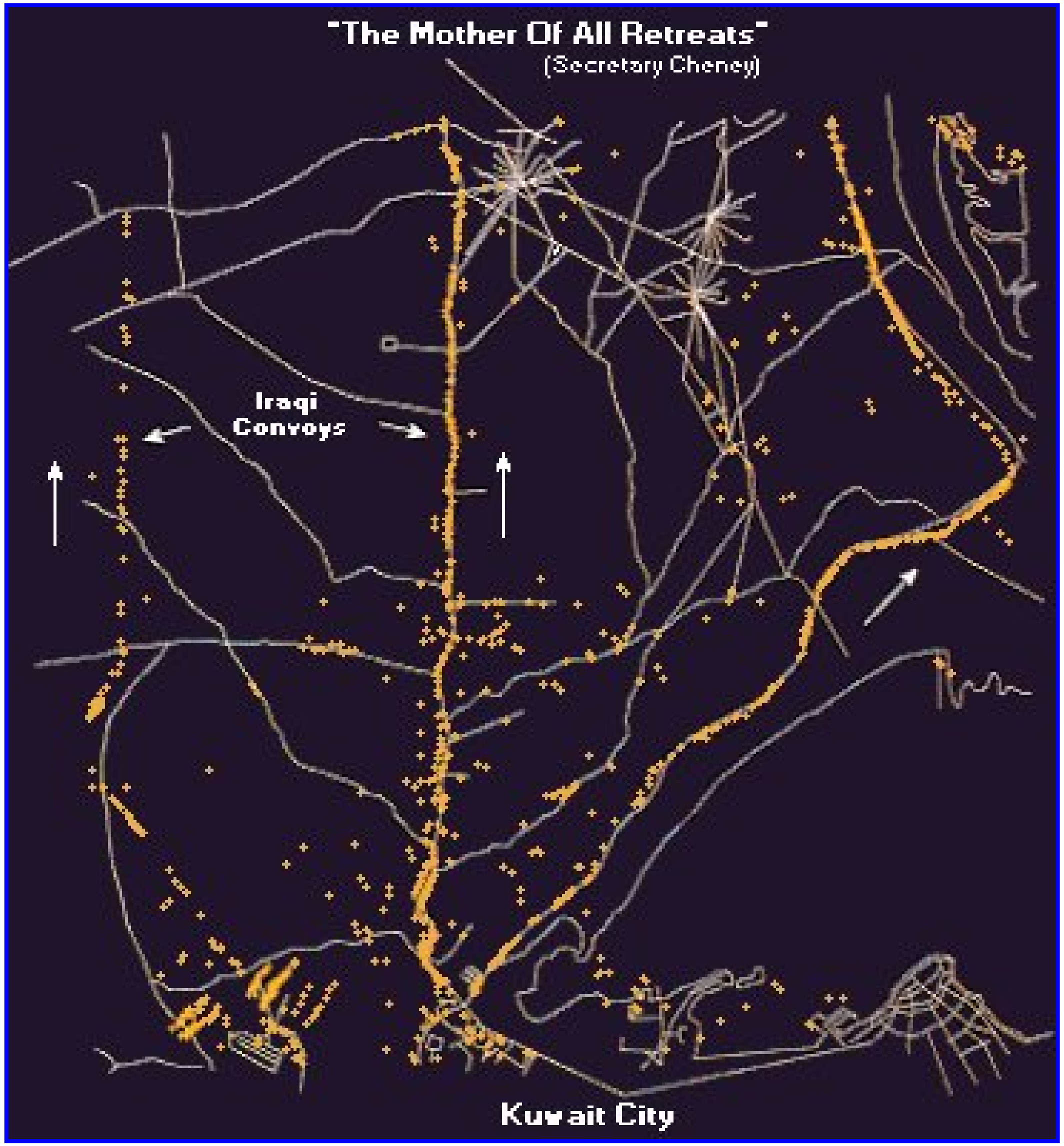
Courtesy of Northrop Grumman
Used with Permission

- **Radar employs a slotted array antenna 24 ft by 2 ft**
  - **456 x 28 horizontally polarized elements**
  - **Beam scans± 60° in azimuth; mechanically rotated in elevation**
- **Aperture can be used as a whole for SAR mapping**
- **When total aperture is divided into 3 independent apertures in the interferometric mode, it is used for moving target detection**
  - **Moving targets are separated from clutter by different time of arrivals of target and clutter in the 3 apertures**
  - **DPCA techniques are used to cancel main beam clutter**

Joint Stars Moving Target Detections

Operation Desert Storm

(Feb 1991)



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Outline

- Introduction
  - The airborne radar environment
- Different airborne radar missions
  - Pulse Doppler radar in small fighter / interceptor aircraft
    - F-14, F-15, F-16, F-35
  - Airborne, surveillance, early warning radars
    - E-2C (Hawkeye), E-3 (AWACS), E-8A (JOINT STARS)
  - Airborne synthetic aperture radar
    - SAR basics to be covered in lecture 19
    - Military and civilian remote sensing missions
      - To be covered in lecture 19, later in the course
- Summary

Detection of Ground Moving Targets

- Ground Moving Target Indication (GMTI)
  - Low or medium PRF pulse Doppler radar used
  - PRF chosen so that Doppler region of interest is unambiguous in range and Doppler
  - K_u (16 GHz) or K_α (35 GHz) Band often used, since fixed minimum detectable Doppler frequency will allow detection of lower velocities than X band
  - APG-67 (X-Band) in F-20 fighter has GMTI mode using medium PRF
  - AWACS has low PRF ship detection mode
- Side-Looking Airborne Radar (SLAR)
  - Standard airborne radar subtracts sequential conventional images of terrain (Non-coherent MTI) to detect moving targets

Detection of Ground Moving Targets

- Synthetic Aperture Radar (SAR) with MTI
  - SARs (discussed in lecture 19) produce excellent images of fixed targets on the ground
    - Good cross range resolution obtain by processing sequential target echoes as aircraft moves a significant distance L
      - Cross range resolution inversely proportional to L not antenna size D
  - Moving targets distorted and smeared in SAR image
  - Can be detected if target Doppler is greater than bandwidth of clutter echo
  - Requires high PRF to avoid aliasing issues

- Joint Stars
  - Uses interferometer for clutter suppression processing

Summary

- **Difficult ground clutter environment is chief radar design driver for airborne radars**
  - Elevated radar platform implies ground clutter at long range
  - Both Doppler frequency of clutter and its spread depend on radar platform motion and scan angle
- **Clutter challenges with Airborne radars**
  - Antenna aperture size often limits frequencies, so that ambiguous range and Doppler velocity issues arise
    - Low, Medium and High PRF Modes each have unique clutter issues
  - Doppler spreading of ground clutter, particularly at broadside, viewing can degrade performance
- **Sophisticated clutter suppression techniques can alleviate some of these issues**
  - DPCA techniques
  - Medium and High PRF modes often imply higher power
- **Active Electronically Scanned arrays and advanced signal processing techniques (STAP) offer significant new capabilities for airborne radars**

Homework Problems

- **From Skolnik (Reference 1)**
  - **Problems 3-19, 3-20, 3-21, 3-22, 3-23, and 3-24**
  - **Show that the maximum Doppler frequency of ground clutter as seen by an airborne radar is**

$$f_D \leq \frac{2V}{\lambda}\left(1 - \frac{h^2}{R^2}\right)$$

Where:

V = velocity of airborne radar
λ = radar wavelength
h = height of radar above ground
R = slant range

  - **Show that, for an airborne radar flying at a constant height above the ground, the lines of constant clutter velocity are a set of hyperbolae**

The last problem is from Roger Sullivan's previously referenced text

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Acknowledgements

- Niall J. Duffy
- Dr. Allen Hearn
- Mark A. Weiner