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Active Phased Array Radar Systems

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Radar Systems

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Outline

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- *Radar System Components*
  - *Definition of Active Phased Array Radar System*
  - *Benefits of Active Array*
  - *Active Array System Design and Analysis*
- *Advanced Active Array Architecture*
  - *Definition of Digital Phased Array Radar System*
  - *Benefits of Digital Array*
  - *Examples of Phased Array Radar Systems*
- *Polarimetric Phased Array*
  - *Definition of Dual pol Configurations*
  - *Benefits of Dual pol Phased Array*
- *Multi-Mission Phased Array Enablers*
  - *Simultaneous Multi Beams (DBF)*
  - *Multi Frequencies*
- *System Cost and Maintenance Considerations*

What is an 'Active' Phased Array?

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- *Basic definition: an array of radiating antenna elements having transmit and receive active components at each element (T/R modules)*
  - *High-power amplifiers (HPA) for transmit*
  - *Low-noise amplifiers (LNA) for receive*
  - *Monolithic Microwave Integrated Circuits (MMIC)*
- *Solid-state semiconductor components provide signal gain - not vacuum tubes*
  - *Solid-state technologies generally associated with the substrate material*
    - *Gallium Arsenide (GaAs)*
    - *Silicon Germanium (SiGe)*
    - *Silicon Carbide (SiC)*
    - *Gallium Nitride (GaN)*
  - *Tube technologies*
    - *Klystron*
    - *Cross-field amplifiers (CFA)*
    - *Traveling wave tube (TWT)*

Active Radar Major Components

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- *Antenna*
  - *Radiating elements*
  - *T/R module*
  - *Beamformer*
  - *Beam steering computer*
- *Exciter (waveform generator)*
- *Receiver (RF signal to digital)*
- *Signal Processor (target detection processing)*
- *Radar Controller (Synchronize, Control and schedule radar operation)*

Radar System Configurations

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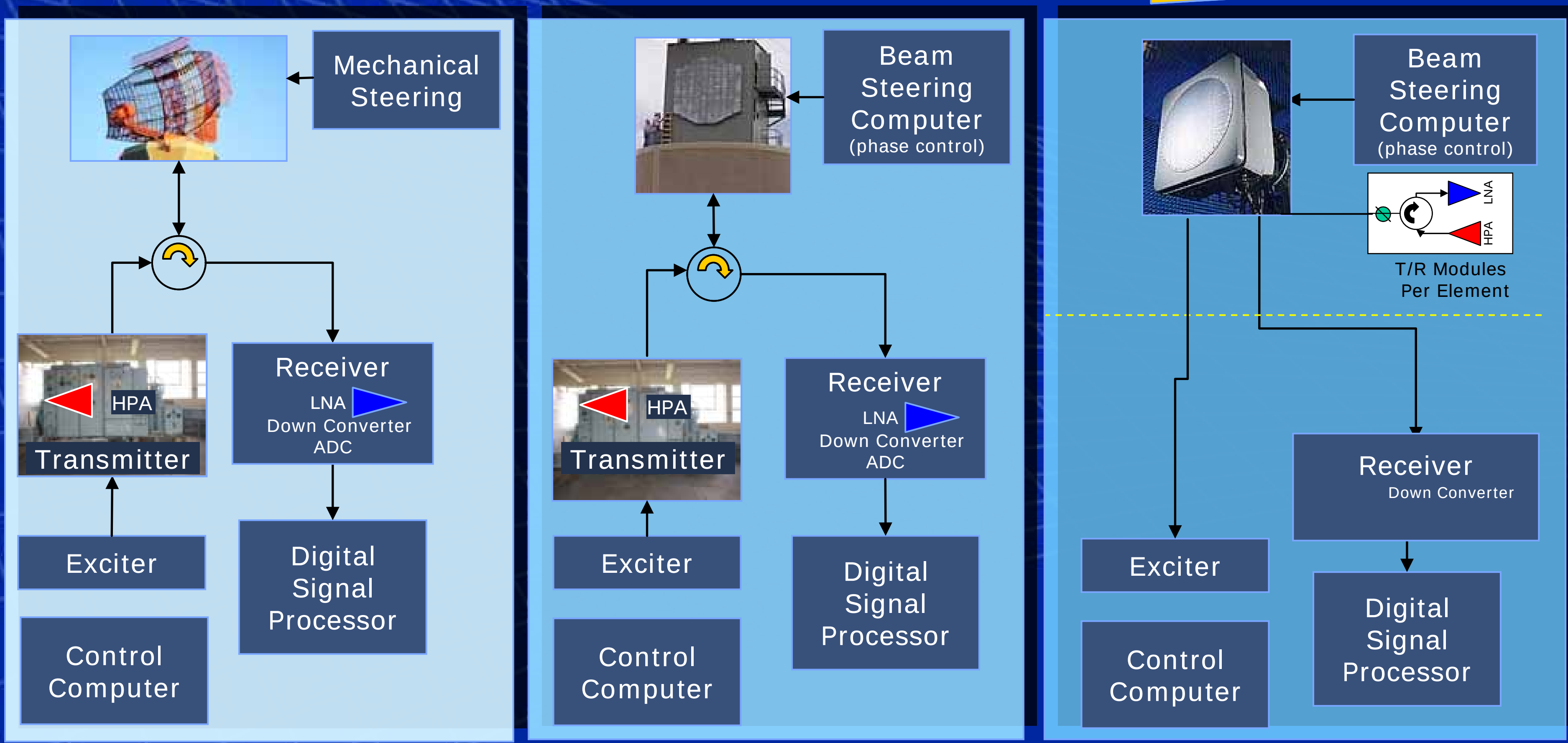
Radar System Design Evolution Over Time

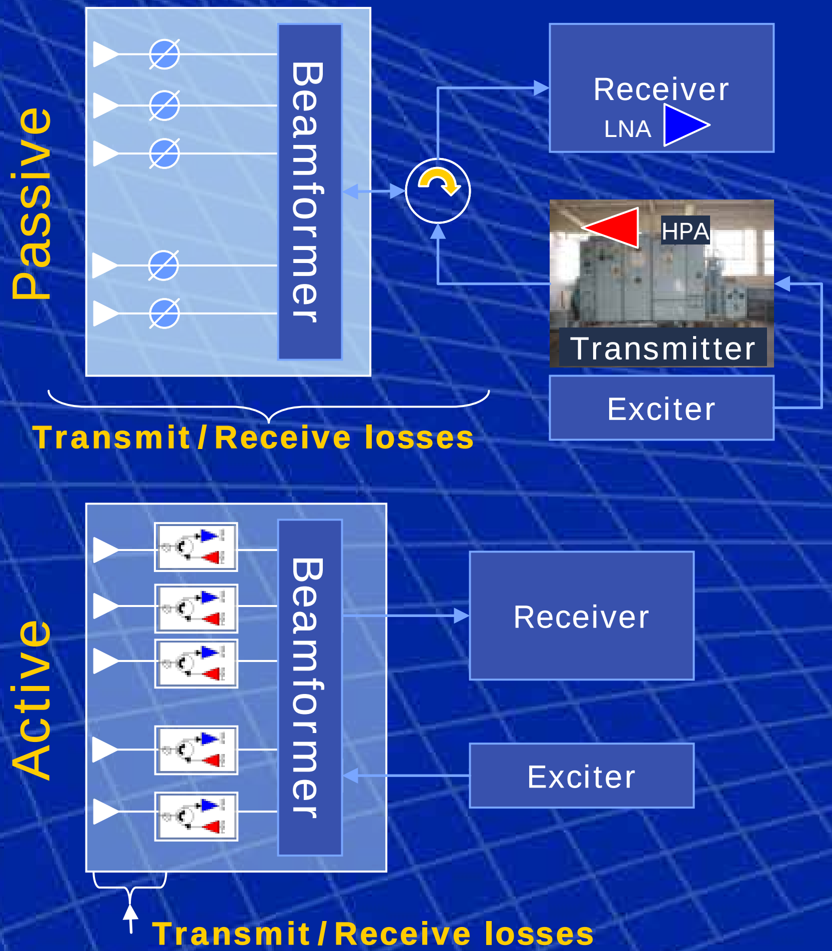


Passive Rotating Dish Radar System

Passive Phased Array Radar System

Active Phased Array Radar System

Key Active/Passive Design Differences



- *Passive*
  - *Antenna driven by single large transmitter amplifier (HPA)*
  - *First receive LNA after beam is formed*
  - *Large signal loss between radiating element and transmitter/LNA*
  - *Antenna connects to transmitter and receiver*

- *Active*
  - *T/R module behind each radiating element*
  - *Transmitter distributed through antenna in many small HPAs*
  - *First LNA distributed through antenna in many small LNAs*
  - *Small signal loss between HPA/LNA and radiating element*
  - *Antenna is transmitter and receiver*

Active Antenna is HPA and LNA –
Passive Antenna Connects to HPA and LNA

Active Array Radar System Benefits Summary

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- *Design and operation*
  - *Replace waveguide (radar plumbing) with cables*
  - *No tube warm-up time or pulsing limitations*
- *Reliability*
  - *Mean-time between failure generally higher (better) for solid-state electronics than tubes*
  - *Graceful degradation performance with component failures*
- *Performance*
  - *Noise figure - > improved detection sensitivity*
  - *Clutter attenuation - > improved detection sensitivity in the presence of clutter*
- *Enabler of digital beamforming*

Active Antenna Noise Figure Benefits

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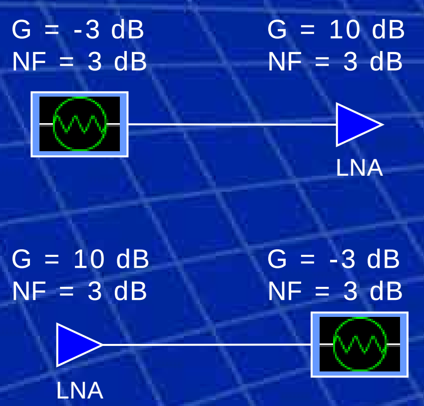
- *Noise figure of a component or system is characteristic of signal-to-noise ratio degradation through the component*
- *First active component in receive chain sets the noise figure*
- *Placing active components before lossy passive components improves noise figure*



$$NF_{chain} = NF_1 + \frac{NF_2 - 1}{G_1}$$

	Gain (dB)	NF (dB)
Loss	-3	3
LNA	10	3
Net	7	6

	Gain (dB)	NF (dB)
LNA	10	3
Loss	-3	3
Net	7	3.21

Example: Lower noise figure when LNA is placed before the Lossy component

Active Array Has Detection Sensitivity Benefits Due to Location of Receiver LNA Upfront in Receiver Chain

Clutter Attenuation

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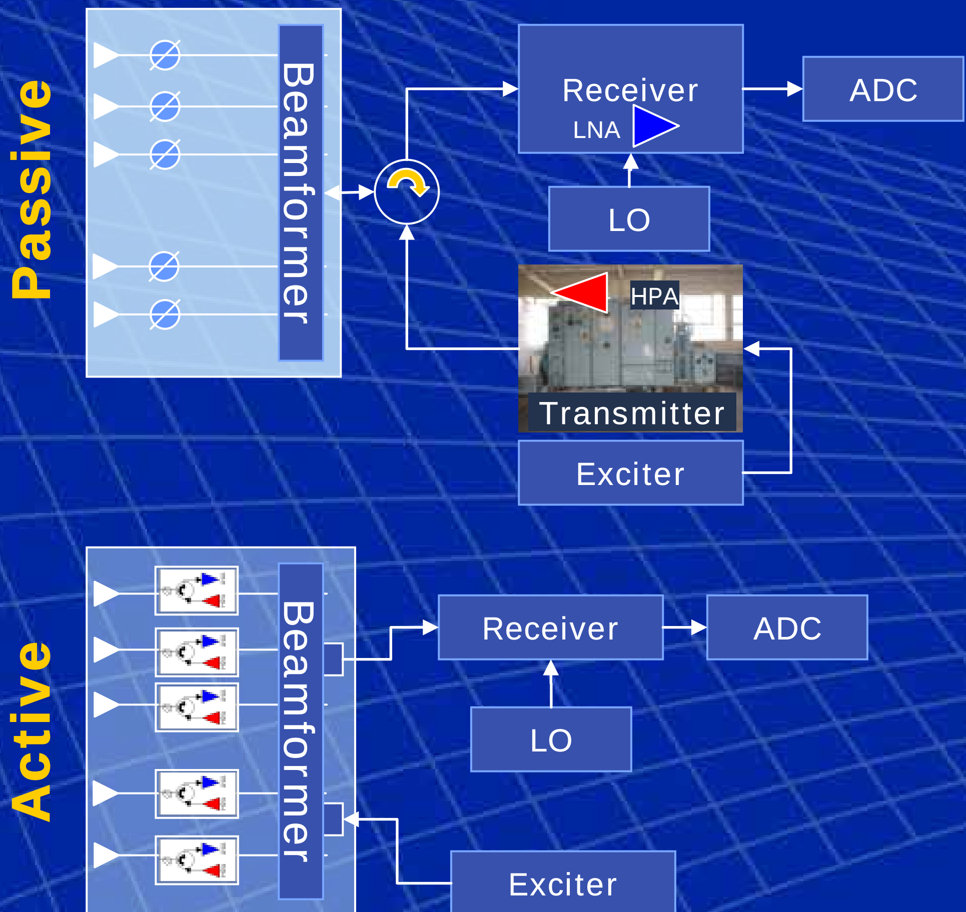
- ***System capability to reduce clutter interference is limited by hardware instability errors***
  - ***Pulse to pulse phase/amplitude errors***
  - ***Intra-pulse noise***
- ***Significant contributors***
  - ***Analog-digital converter (ADC)***
  - ***Down-conversion 1st Local Oscillator (LO)***
  - ***High-power amplifiers (HPA)***
  - ***Low-noise amplifiers (LNA)***
  - ***Exciter/waveform generator***
- ***Active Antenna improves system clutter attenuation***
  - ***Errors de-correlate across distributed HPA/LNA***

Active Antenna Benefits to Clutter Attenuation



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	Active System	Passive System
Exciter	60	60
Transmitter	80	50
HPA	*50*	*50*
N HPA	*1000*	*1*
Receiver	69.6	50.0
LO	70	70
LNA	50	50
N LNA	1000	1
ADC	60	60
System	**56.7**	**46.6**

Example: Clutter attenuation improved by distributed amplifier error de-correlation

$$\frac{1}{CA_{sys}} = \frac{1}{CA_{exciter}} + \frac{1}{CA_{transmitter}} + \frac{1}{CA_{receiver}} + \frac{1}{CA_{ADC}}$$

$$\frac{1}{CA_{transmitter}} = \frac{N_{HPA}}{CA_{HPA}}$$

$$\frac{1}{CA_{receiver}} = \frac{1}{CA_{LO}} + \frac{N_{LNA}}{CA_{LNA}}$$

Active Array Enables Higher System Clutter Attenuation Due to Distributed HPA/LNA Architecture

Performance Analysis Example

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- *Example systems with representative parameters*
  - *Passive*
    - *1000 elements*
    - *1 Mega-watt transmitter*
    - *1% transmit duty*
    - *10 kW average power*
    - *20 kW prime power at 50% PAE*
  - *Active*
    - *1000 elements*
    - *5 W T/R module*
    - *10% transmit duty*
    - *500 W average power*
    - *2 kW prime power at 25% PAE*

	Passive	Active
T/R Module Power - Watts		5
Number of Elements	1000	1000
Gain of Element - dB	3.00	3.00
Transmit Power (Pt) - Watts	100000	5000
Transmit loss (Lt) - dB	3	1.5
Receive Gain (Gr) - dB	30	30
Receive loss (Lr) - dB	3	1.5
System Noise temperture (Tsys)	1000	1000
Transmit Duty (Du)	1%	10%
Round-trip Sensitivity Factor	24.0	24.0

$$\text{Roundtrip Sensivity Factor} := \frac{P_t D_u G_t G_r}{T_{sys} L_t L_r}$$

$$R^4 = \frac{P_t G_t G_r \lambda^2 \sigma \tau}{(4\pi)^3 SNR_{\text{det}} k T_{sys} L_t L_r L_{sigpro} L_{\ldots}}$$

Equal detection performance:
Passive system – high-peak power, low duty
Active system – low-peak power, high duty

Active and Passive Radar Systems Can Be Designed to Provide Same Detection Performance With Different Operating Methodologies

Active Antenna Enables Digital Beamforming

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- ***Digital beamforming is digitization of radar signal at the radiating element / sub-array level***
- ***Beams are formed in digital domain using digital computation hardware***
  - ***Number of beams formed constrained by computation latency and data throughput***
- ***Digital beamforming affords multiple simultaneous beams and improved System instantaneous dynamic range (IDR) and clutter attenuation***
- ***Multiple beams can be employed in analog beamforming***
  - ***Additional RF losses (degraded detection sensitivity)***
  - ***RF hardware complexity to incorporate multiple beam analog networks***

Advanced System Configurations

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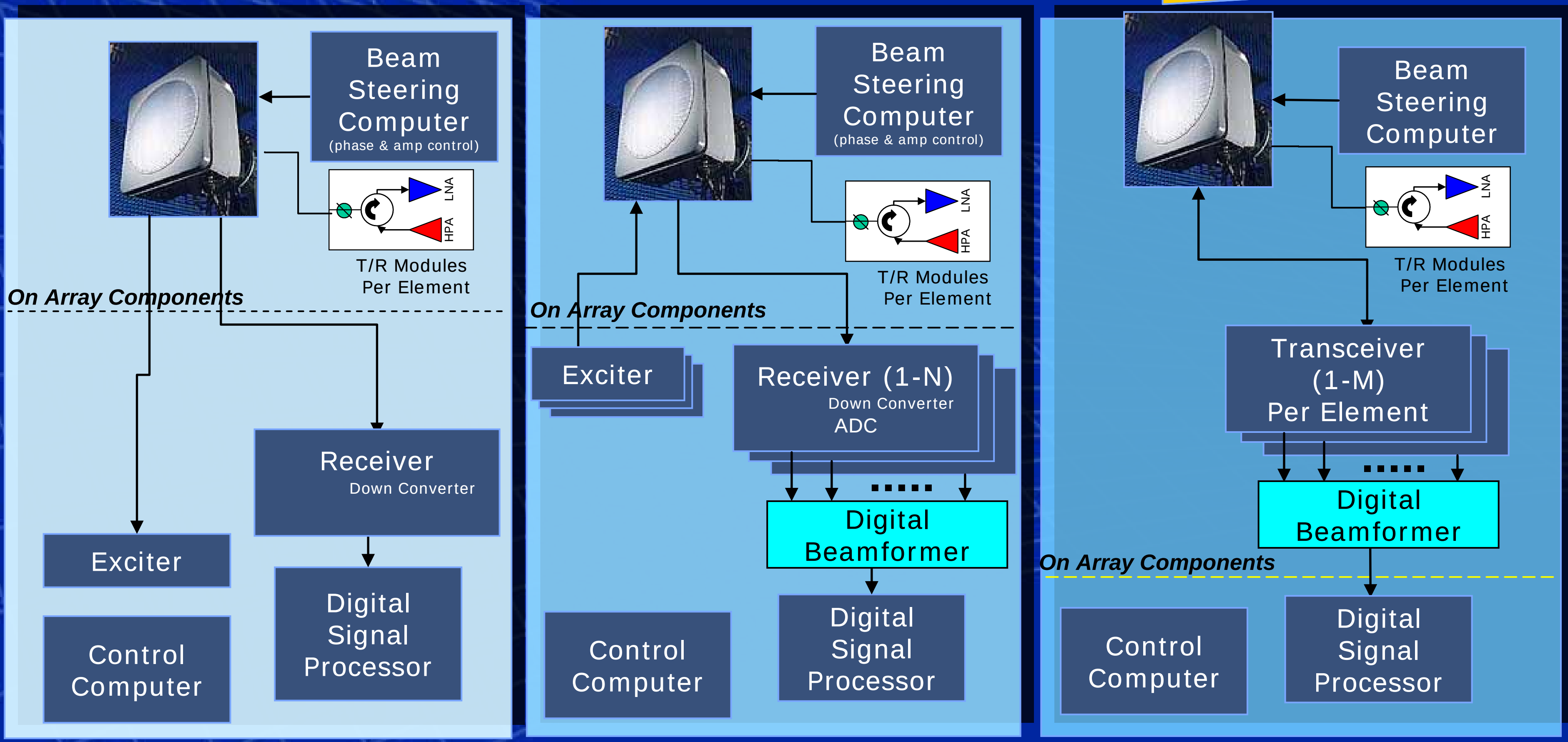
Advancement in Active Phased Array Architecture



Active Phased Array Radar System

Digital at Subarray Level Radar System

Digital at Element Level Radar System

Future Work Trends

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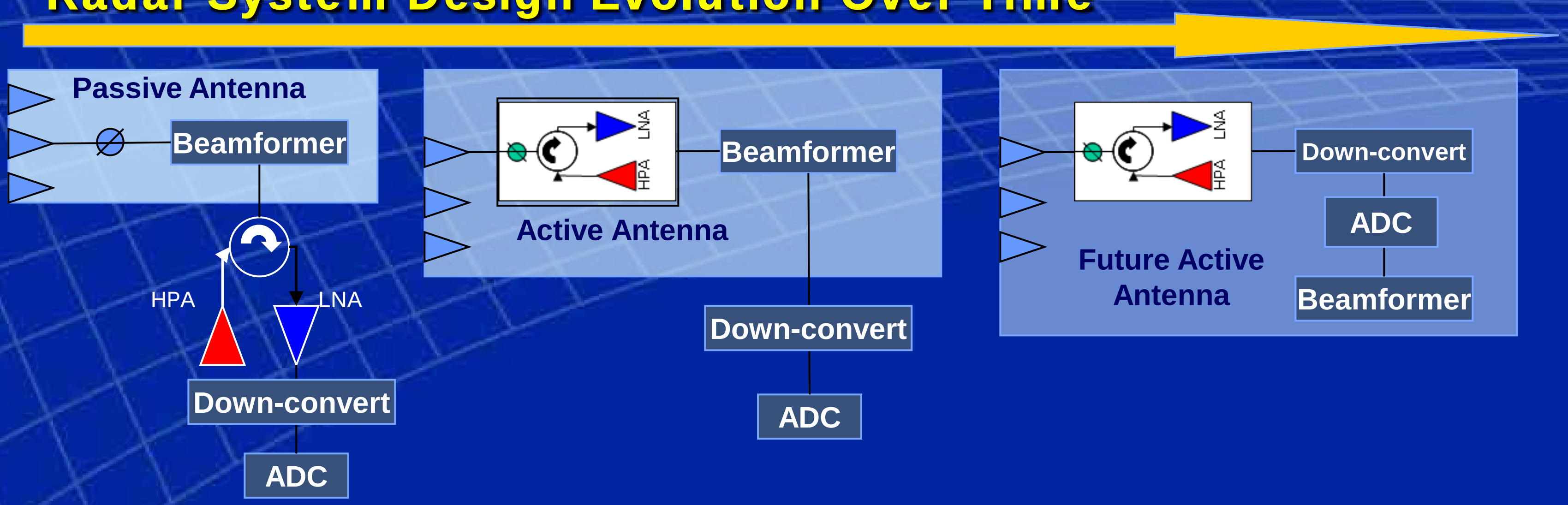
- *Everything gets smaller, lighter*
- *More components get integrated inside Antenna*
  - *All transmitter, receiver, exciter equipment condensed into the Antenna 'box'*
    - *Move A/D converter closer to radiating element – improves system dynamic range*
  - *All digital beam-forming done inside the Antenna 'box'*
  - *Digital beam-forming introduces capability of multiple simultaneous formed beams*
- *Wide-band gap HPA devices (example SiC T/R Modules)*
  - *Higher T/R module output power*
  - *Higher efficiency*

Radar System Design Evolution Over Time



Benefits of Digital Beam-forming: Multiple Simultaneous Beams

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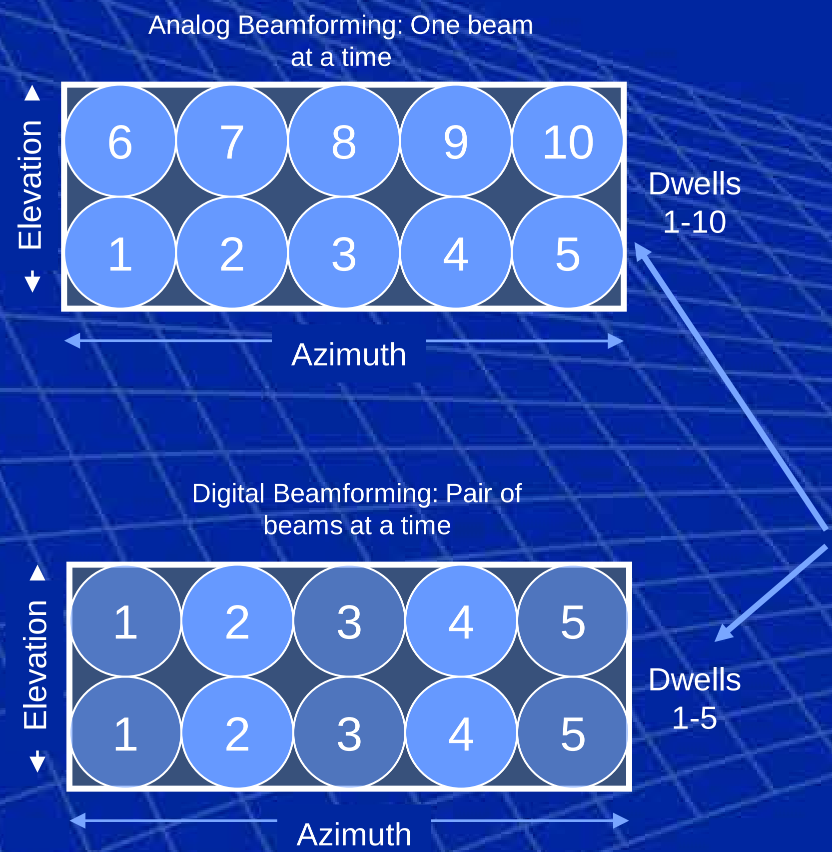
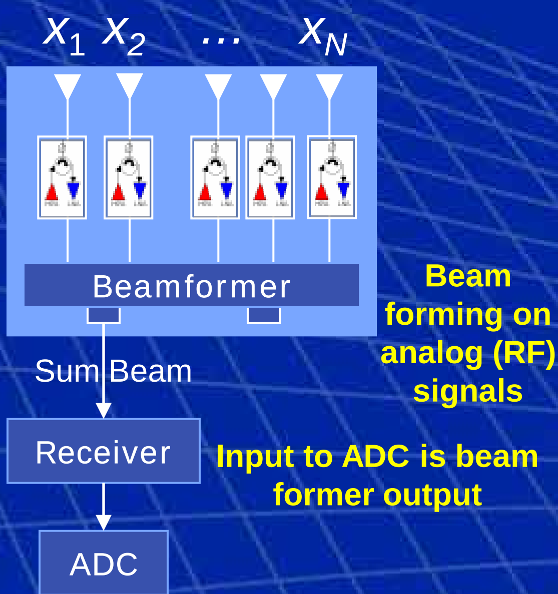


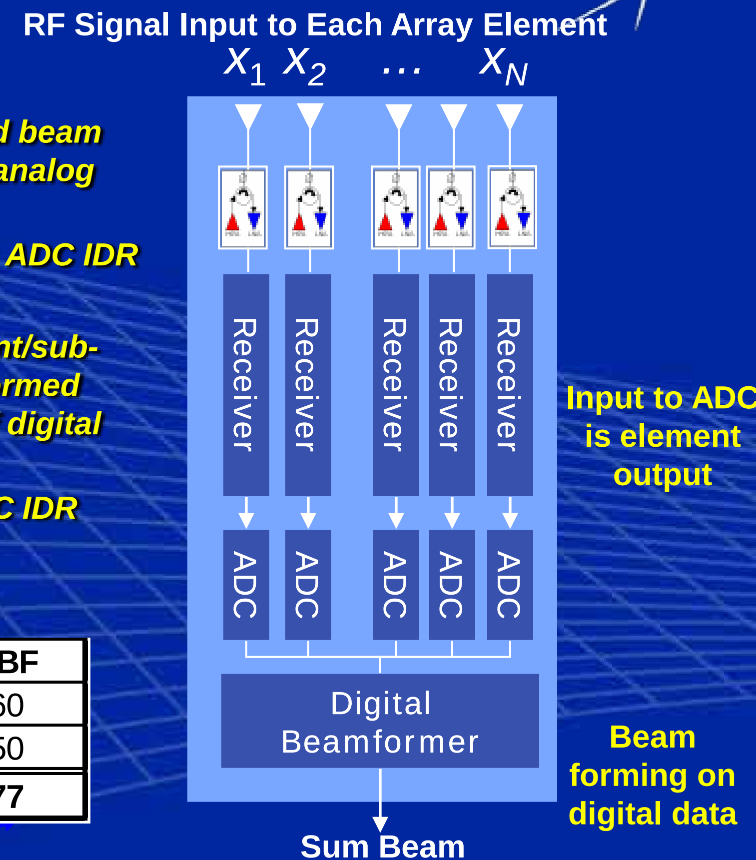
- ***Cover same volume with fewer dwell positions***
- ***Additional radar timeline made available***
  - ***Shorter frame time -> quick target detection***
  - ***Longer waveform integration -> higher detection sensitivity, clutter mitigation***
  - ***Incorporate multiple simultaneous radar functions***
- ***Example: Number of dwell locations reduced by factor of 2 via multiple digital beams***
  - ***Increase waveform integration time by 2X – or -***
  - ***Reduce search frame time by 2X***

Digital Beam Forming Affords Simultaneous Beams – Benefits Radar Timeline

Benefits of Digital Beamforming: Dynamic Range



- *Analog beam forming:*
  - *Input to ADC is formed beam signal: summation of analog signals*
  - *System IDR limited by ADC IDR*
- *Digital beam forming*
  - *Input to ADC is element/sub-array analog signal: formed beam is summation of digital signals*
  - *System IDR is N X ADC IDR*



	ABF	DBF
ADC IDR (dB)	60	60
N ADC	1	50
System IDR (dB)	**60**	**77**

Example: IDR improved by distributed ADC, further up receive chain

Digital Beam Forming Benefits System Dynamic Range Due to Distributed ADC

Examples of Multi-function PAR Radars

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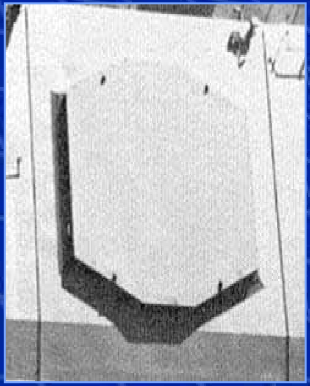
Passive Phased Array



SPY-1A
(1970's)

NWRT
(2003)

Digital Phased Array

R&D
(2006)

Active Phased Array

COBRA
(1980's)

SPY-4 VSR
(2008)

EQ-36
(2010)

Dual Pol Configuration Modes

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- ***Alternating Transmit and Simultaneous Receive (ATSR) Mode***
- ***Simultaneous Transmit and Simultaneous Receive (STSR) Mode***
- ***Alternating Transmit and Alternating Receive (ATAR) Mode***

Alternating Transmit and Simultaneous Receive (ATSR) Mode

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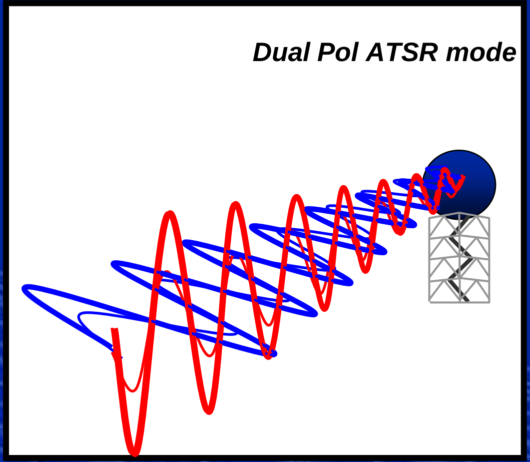
Alternate Transmit and Simultaneous Receive (ATSR) Mode:

- *Vertical pol transmit and simultaneously receive from both polarizations; then*
- *Horizontal pol transmit and simultaneously receive from both polarizations*



- *+ compatibility with existing NCAR algorithms*
- *+ Linear Depolarization Ratio (LDR) can be measured*
- *+ achievable cross polarization isolation (-25 dB)*
- *+ common waveform generator for both polarization*
- *-- need to use switch,*
- *-- requires longer scan time*

Simultaneous Transmit and Simultaneous Receive (STSR) Mode

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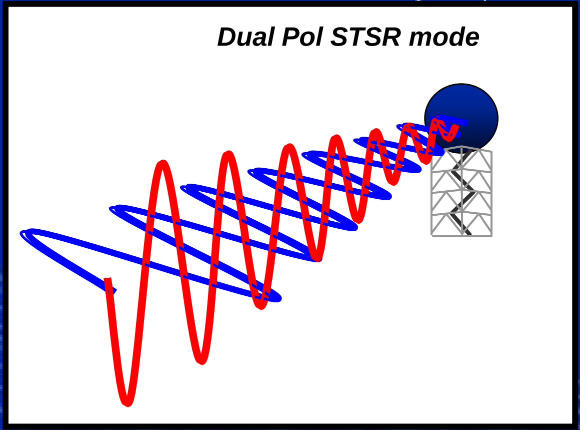

Simultaneous Transmit and Simultaneous Receive (STSR) Mode:

- *Simultaneous independent transmission of two orthogonally polarized channels and simultaneous receive from both channels*

- *+ compatibility with current NEXRAD algorithms*
- *+ provide circular polarization capability*
- *+ efficient scanning time*
- *-- must match/balance two receivers, control gain drifting, temperature*
- *-- challenging cross polarization requirements (-45 dB)*

Alternating Transmit and Alternating Receive (ATAR) Mode

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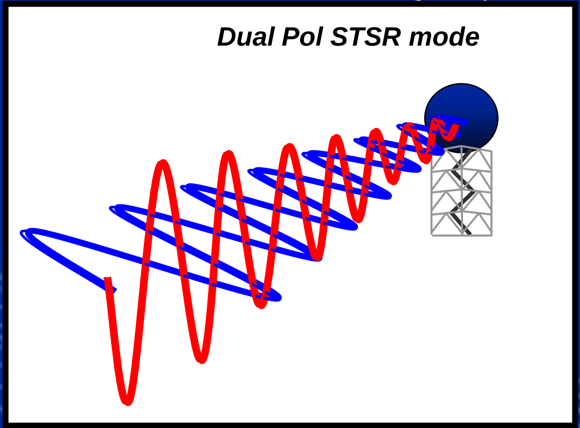

Alternating Transmit and Alternating Receive (ATAR) Mode:

- ***Vertical pol transmit and receive co-polar; then***
- ***Horizontal pol transmit and receive co-polar***

- ***+ achievable cross polarization isolation (-25 dB)***
- ***+ only one receiver required (no need to balance receivers)***
- ***-- -- need to use switch,***
- ***-- requires longer scan time,***
- ***--unsuitable for batch mode, staggered or variable PRTs***

Hardware Implication for Different Dual Pol Configurations

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Relative Cost & Complexity		Single Pol	Dual Pol: Simultaneous Tx Simultaneous Rx	Dual Pol: Alternate Tx Simultaneous Rx	Dual Pol: Alternate Tx Alternate Rx
$$	RF Switch	N/A	N/A	High	High
$$$	Transmit Chain	Low	High	Low	Low
$$	Receive Chain	Low	High	High	Low
$	Digital Beamforming Processing	Low	High	High	Medium
$	Off Array Signal Processor	Low	High	High	Medium
	Over all Cost	$	$$$$	$$$	$$

Multi-Mission Active Radar

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- *With technological advances provided by Solid State Phased Arrays simultaneous scheduling of multiple radar timelines is achievable*
  - *Within a single mission the use of beam spoiling on transmit and DBF on receive can reduce the scan time significantly to support multi-mission operation.*
  - *Across multiple missions, the simultaneous use of multiple frequencies that are sufficiently spaced allows the multiplexing necessary to support multi-mission operation.*

Digital Phased Arrays With Multiple Frequencies Provide the Capabilities for Multi-Mission Operations

Multi Frequency Channels

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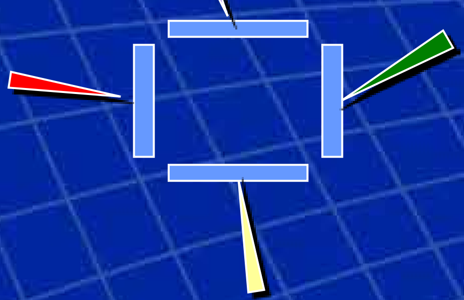
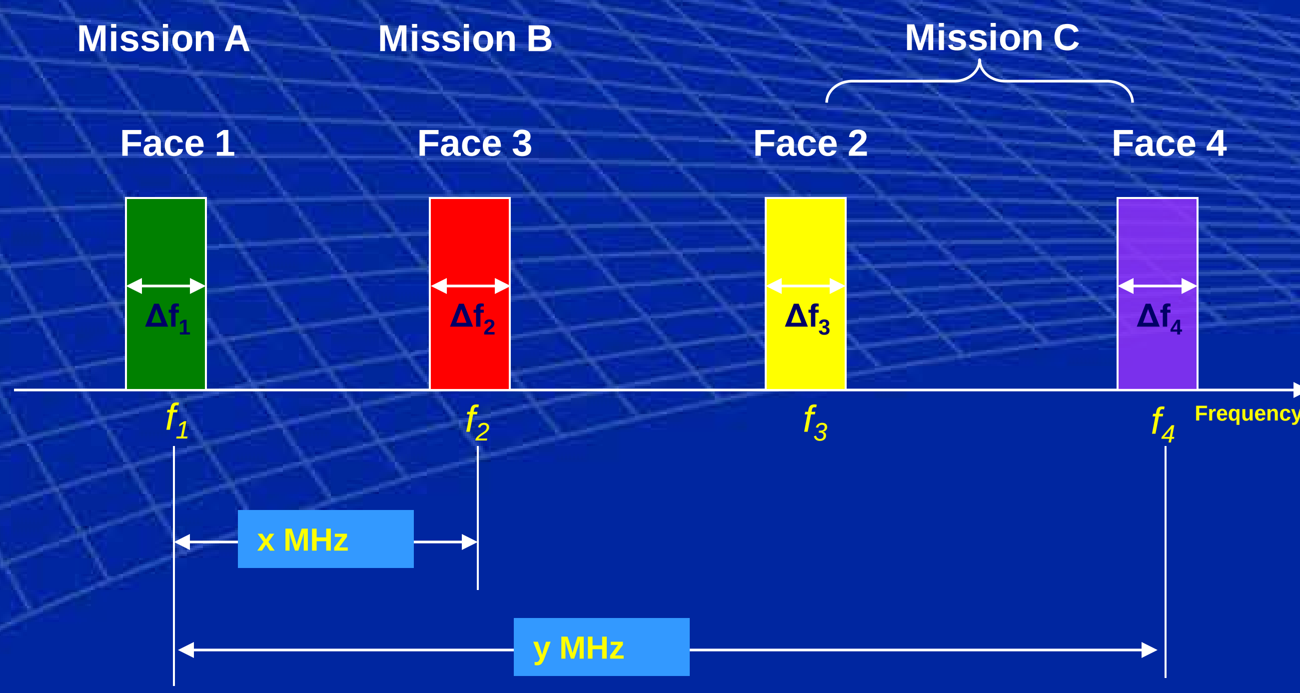
- *Multi frequency channels radar enable multi-mission and multi-face radar operation*
- *Point target operation 10 Mhz frequency separation provides enough isolation for simultaneous multi-mission operation without interference*

4 Active Antenna Fixed Faces (top view)





Δf= Transmitted Pulse Isntantenous Band Width

Active vs. Passive Design Selection Criteria

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- *Selection of an active system based on the performance and functions that are desired from the system and the cost that is desired for the system*
- *Analysis needs to consider cost, performance and reliability*

	Passive	Active
Cost	*More expensive than rotating dish*	*Higher cost than Passive, but has potential cost reduction with time*
Performance	*Low transmit duty – limits functions* *Lower signal stability – limits capability in clutter environments*	*High duty enables more functions* *High signal stability – enhanced capability in clutter environments*
Reliability	*Lower reliability* • *Tube transmitter is potential single-point failure* • *Very High signal levels lead to mechanical switches (i.e. waveguide switches)*	*High reliability –* • *Multiple HPAs distributed, graceful degradation* • *Lower signal levels allow solid-state switches*

Summary

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- *Active Phased Array Antenna has signal transmit and receive amplifiers in the Antenna*
  - *Antenna is the transmitter and receiver*
- *Active arrays provide reliability and performance improvements over passive systems*
  - *All solid-state design and components*
  - *Graceful degradation*
- *Design of active radar systems introduce additional complexities*
  - *Power, cooling, calibration*
  - *Additional requirements on antenna*
- *Active Radar system development is hardly new – Systems exist*
- *Lockheed Martin has produced an advanced solid-state radar demonstrator*
  - *S4R: Risk reduction for near and far term business pursuits*
- *In the future, components will be smaller, lighter and the Antenna will have much more capability*

Keywords

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Term	Definition
ABF	Analog beamforming
ADC	Analog to digital convertor
AESA	Active ESA
Beamformer	Network of microwave dividers and combiners that 'form' the transmit and receive beams of a phased array
CA	Clutter attenuation - measure of stability limitation to mitigate clutter
Circulator	Component that allows one-way signal flow - Transmit direction, receive direction
DBF	Digital beamforming - beamforming done in digital domain using computers as opposed to using analog hardware
Duty factor	Ration of ON time to OFF time
EIRP	Effective isotropic radiated power
ESA	Electronic scanning antenna (array)
Exciter	Generates radar signal, upconverts to microwave signal
HPA	High-power amplifier
IDR	Instantaneous dynamic range - useful signal range
ITOI	Input TOI
LNA	Low-noise amplifier
MMIC	Monolithic microwave integrated circuit
NF	Noise figure - measure of the noise added to a signal by a component
PAE	Power added efficiency
Phase-shifter	Component behind each element in a phased array that steers the beam
Receiver	Processes received radar microwave signal - down-converts and digitizes
SFDR	Spur free dynamic range - measure of useful signal range before distortion
SLL	Sidelobe level of antenna pattern
T/R Module	Self-contained module having solid-state MMICs, HPAs and LNAs
TOI	Third order intercept - measure of distortion introduced by component

Weather Radar and Polarization

- *In general, weather radars send and receive microwaves at one polarization, usually horizontal.*
- *Dual Polarization is used to obtain additional information on the nature of the targets.*
  - *Potential non cooperative target recognition*
- *Comparing the relative strength and phase of the horizontal and vertical returns determines scatters orientation*
- *Three dual pol weather modes of operations:*
  - *Alternate transmit and alternate receive*
  - *Alternate transmit and simultaneous receive (NCAR)*
  - *Simultaneous transmit and simultaneous receive (NEXRAD)*

Benefits of Polarimetric Phase Array Radar for Weather Sensing

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- *Accurate hydrometeor classification*
- *Distinction of rain from other types of hydrometeors*
- *Improved ground clutter cancellation*
- *Improved compensation for reflectivity biases*
- *Estimation of rain fall rate*