Radio Frequency Integrated Circuit (RFIC) Beamforming for Agile, Low-Cost Overlapped Subarrays

Sean M. Duffy, Daniel D. Santiago, Christopher C. Olson, and Jeffrey S. Herd

MIT Lincoln Laboratory

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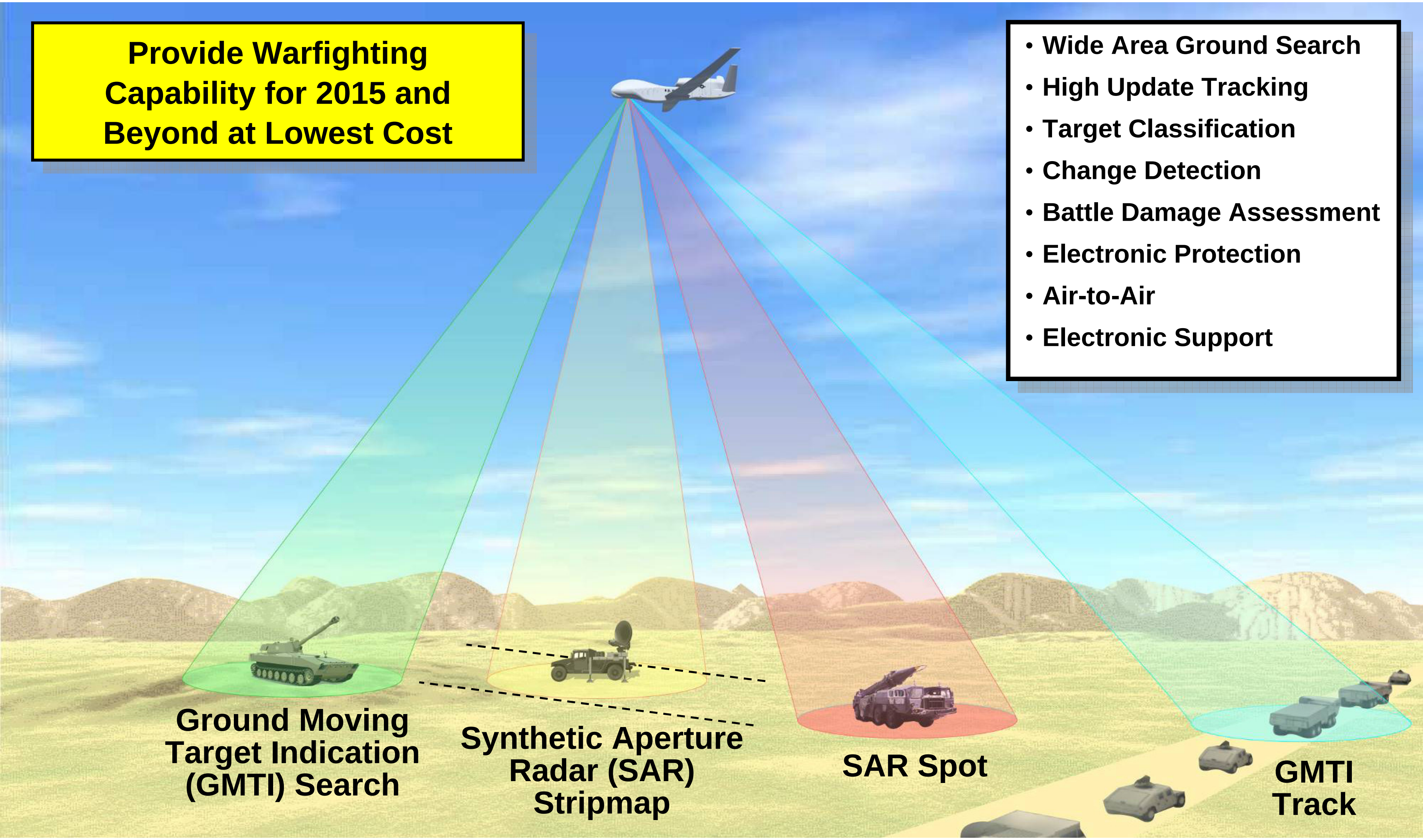
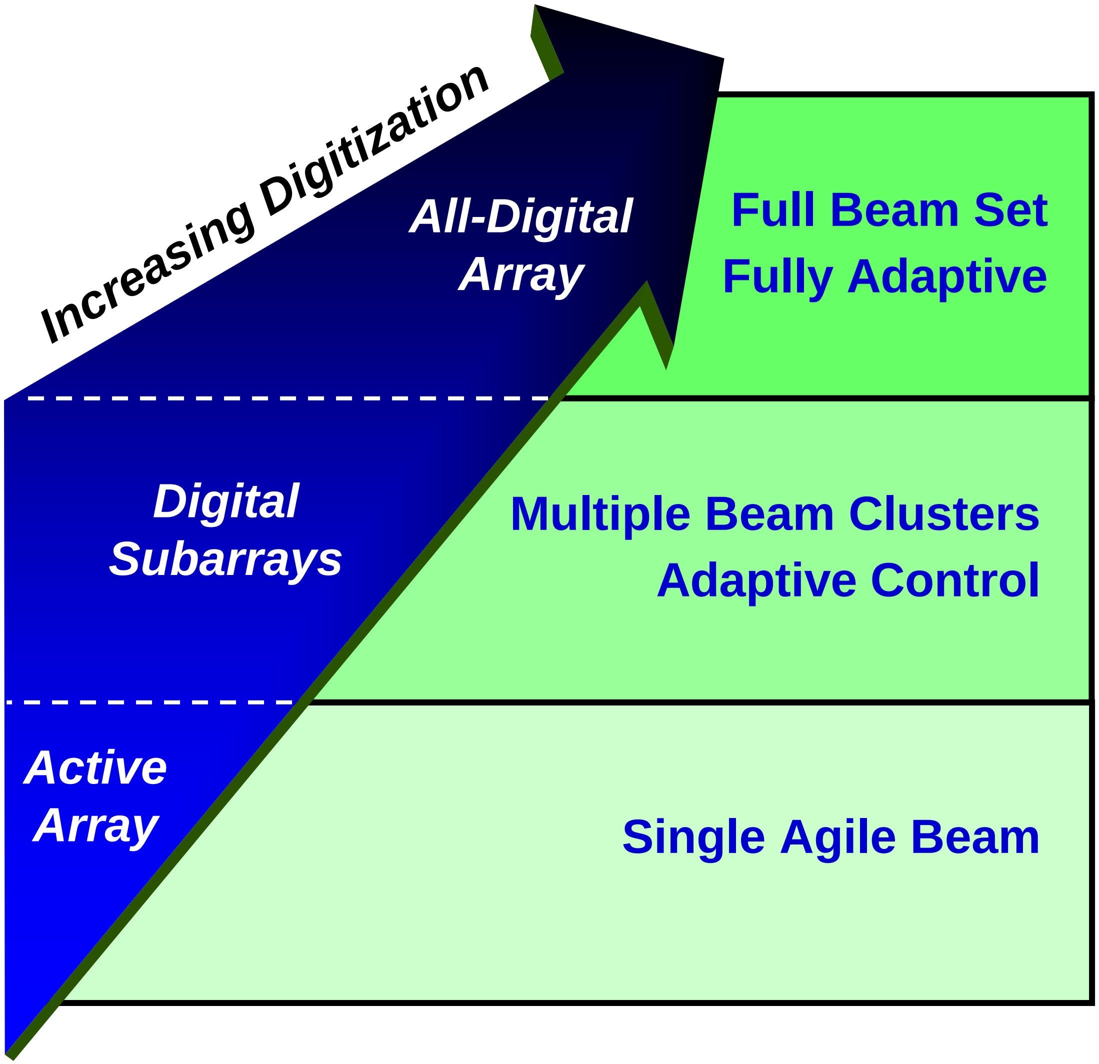
Notional Multi-Mission Sensor Platform

Provide Warfighting Capability for 2015 and Beyond at Lowest Cost

- Wide Area Ground Search
- High Update Tracking
- Target Classification
- Change Detection
- Battle Damage Assessment
- Electronic Protection
- Air-to-Air
- Electronic Support



Antenna Array Architecture Evolution



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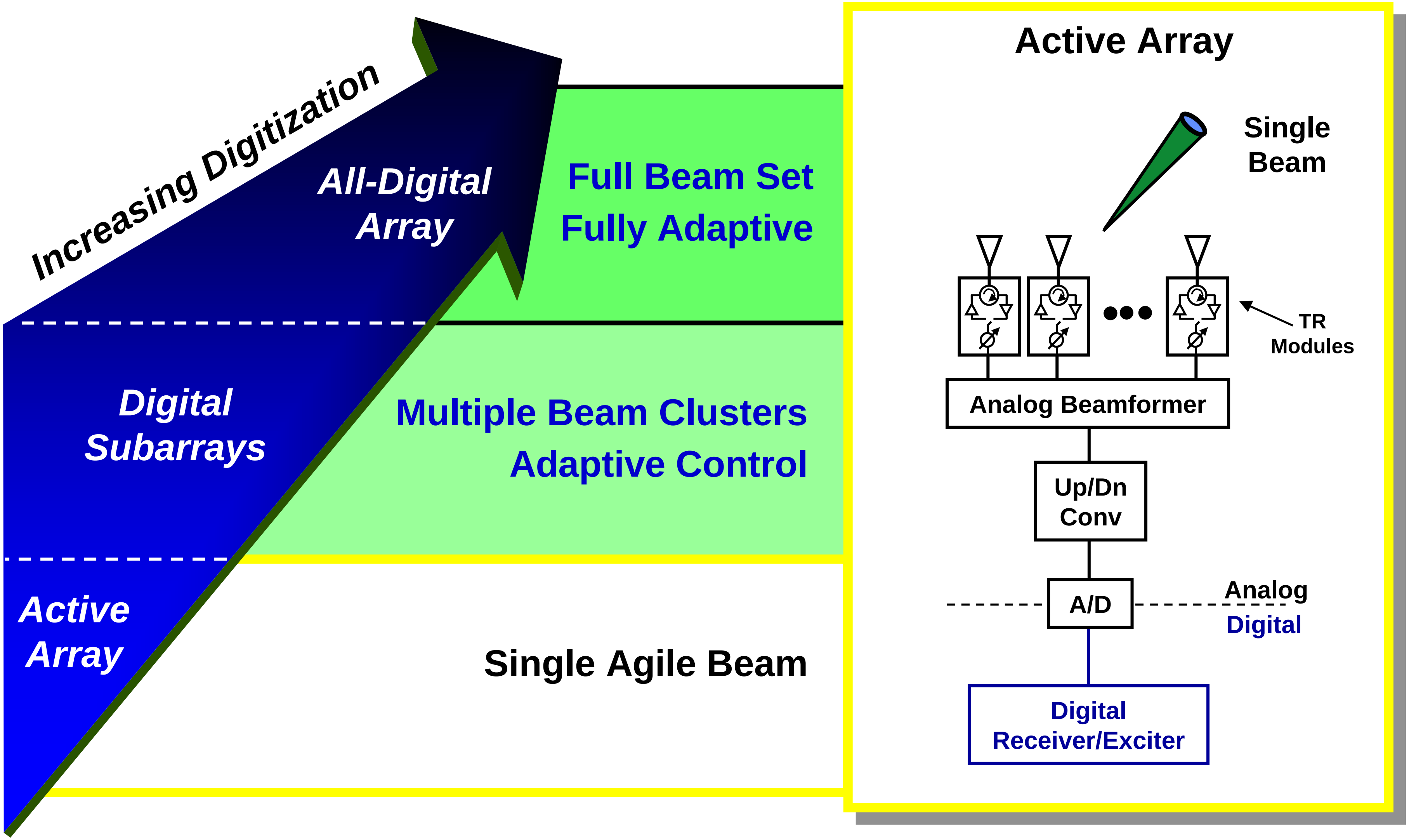

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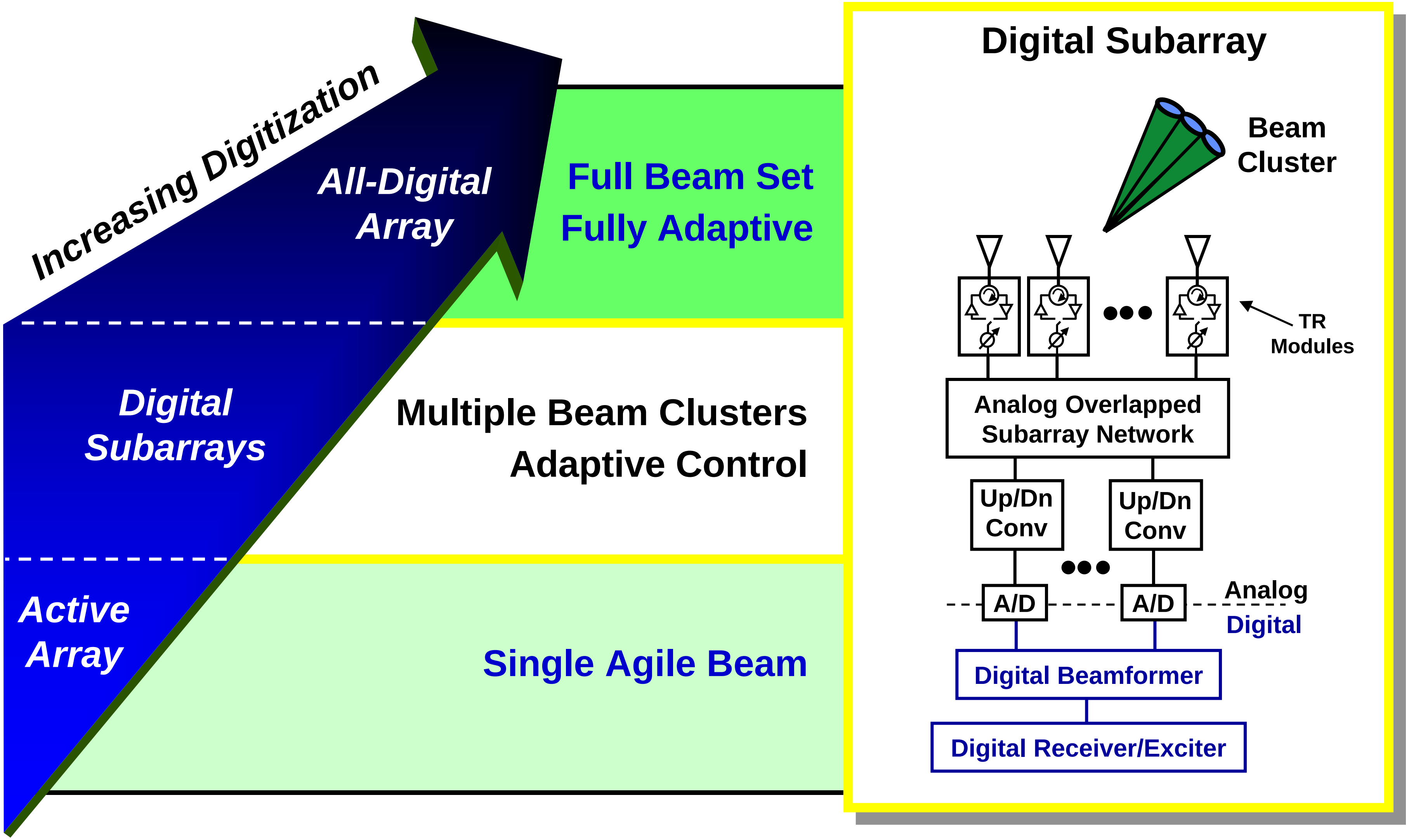

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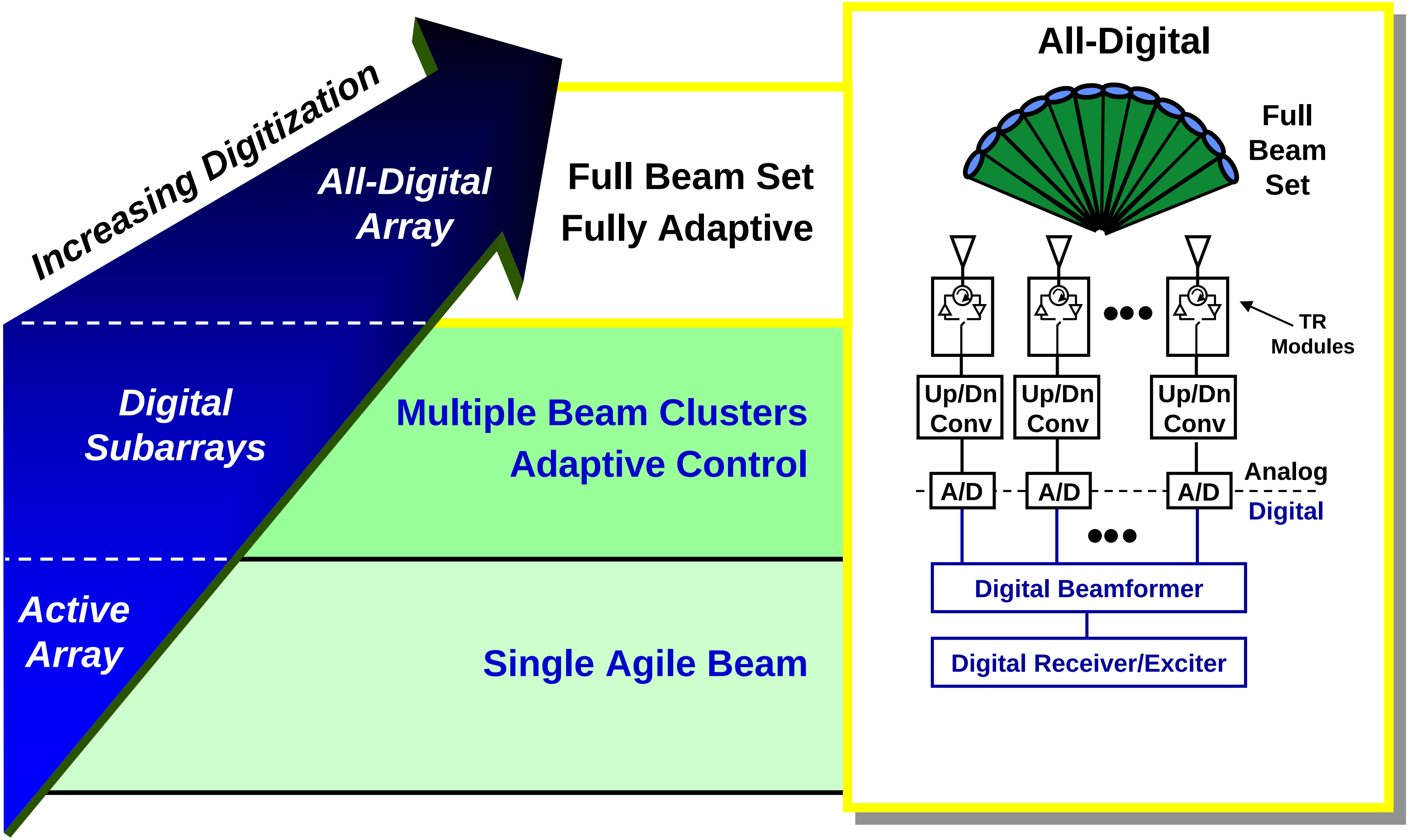
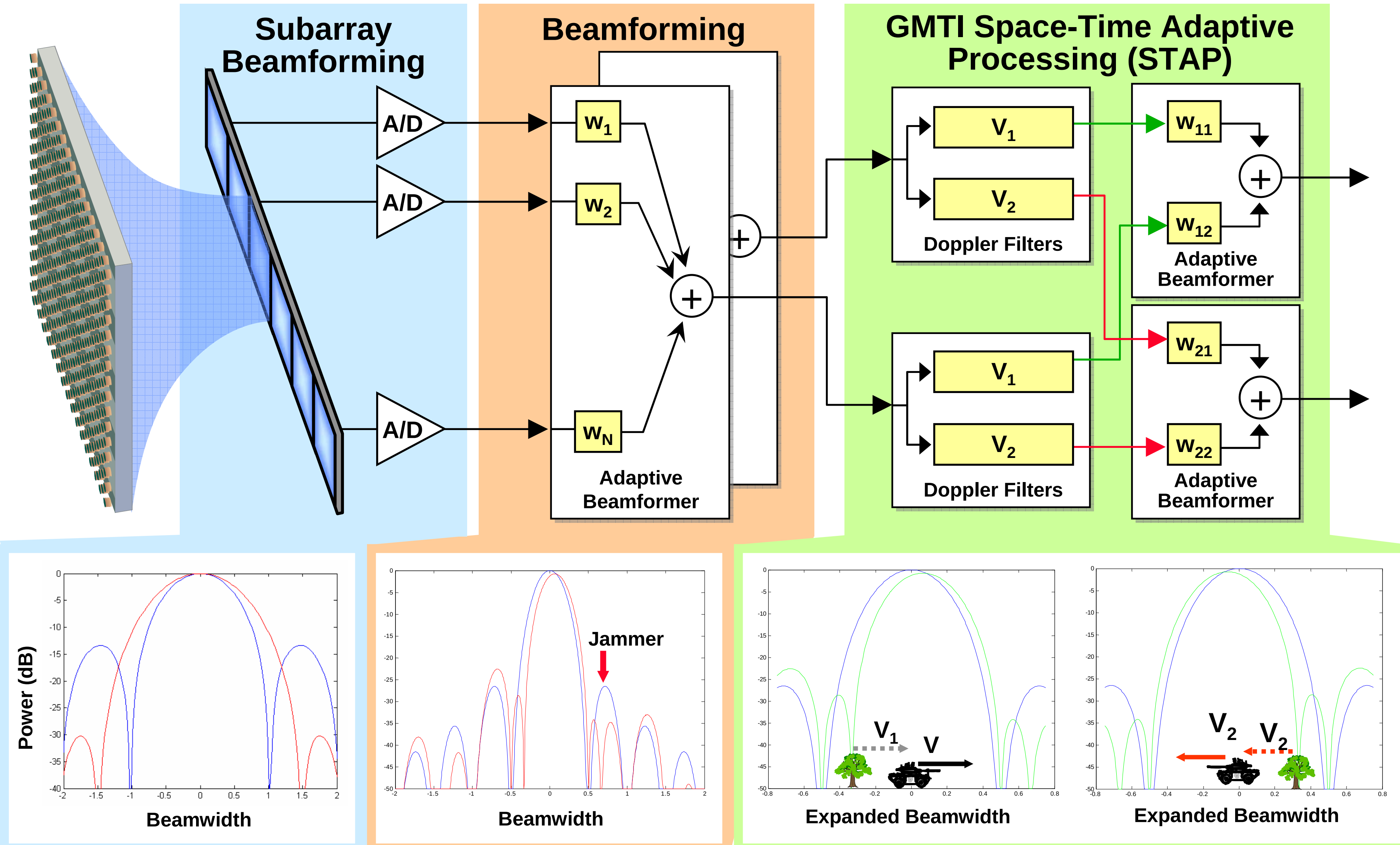
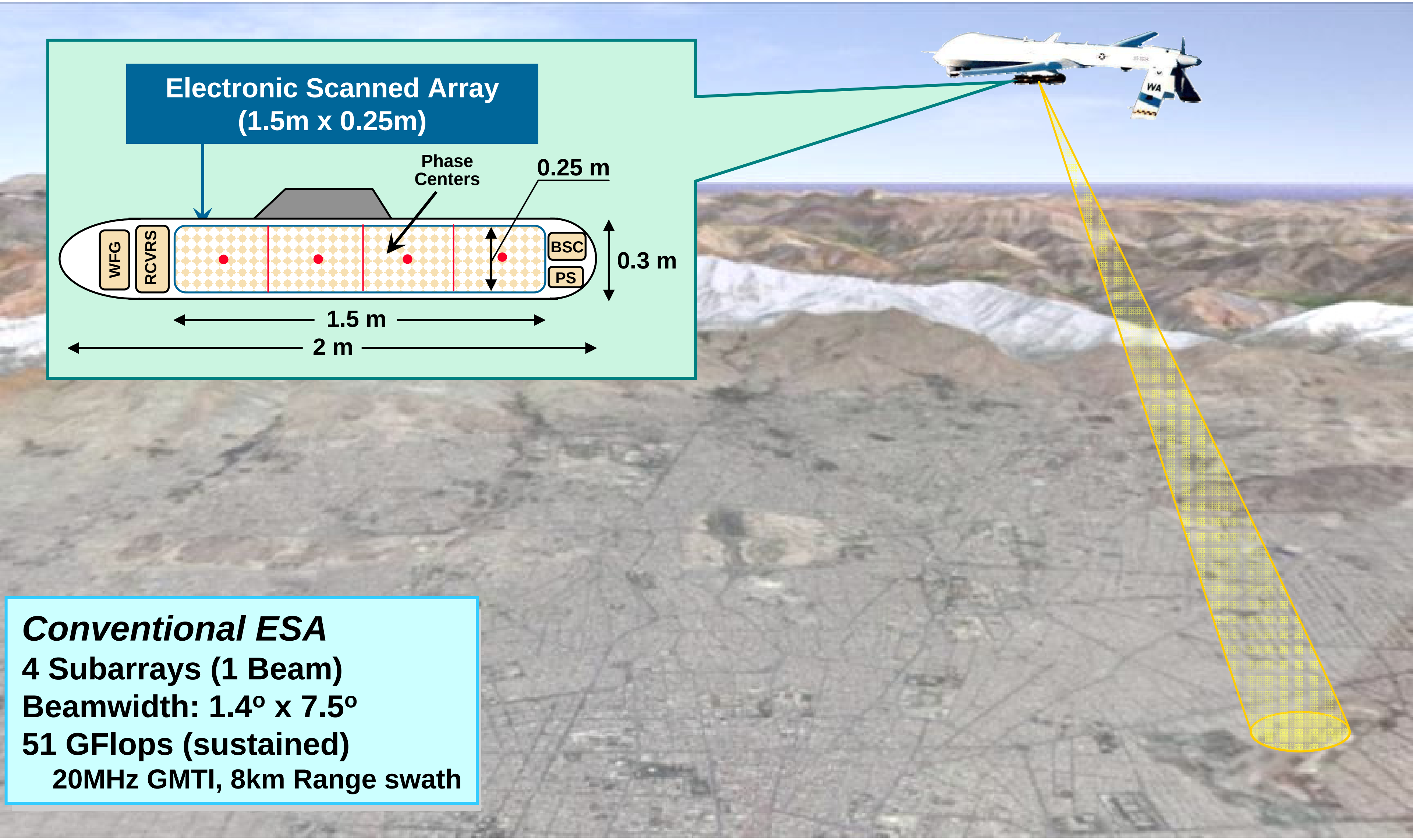


Real-Time Radar Signal Processing Drivers



X-Band Pod Radar Example



Conventional ESA

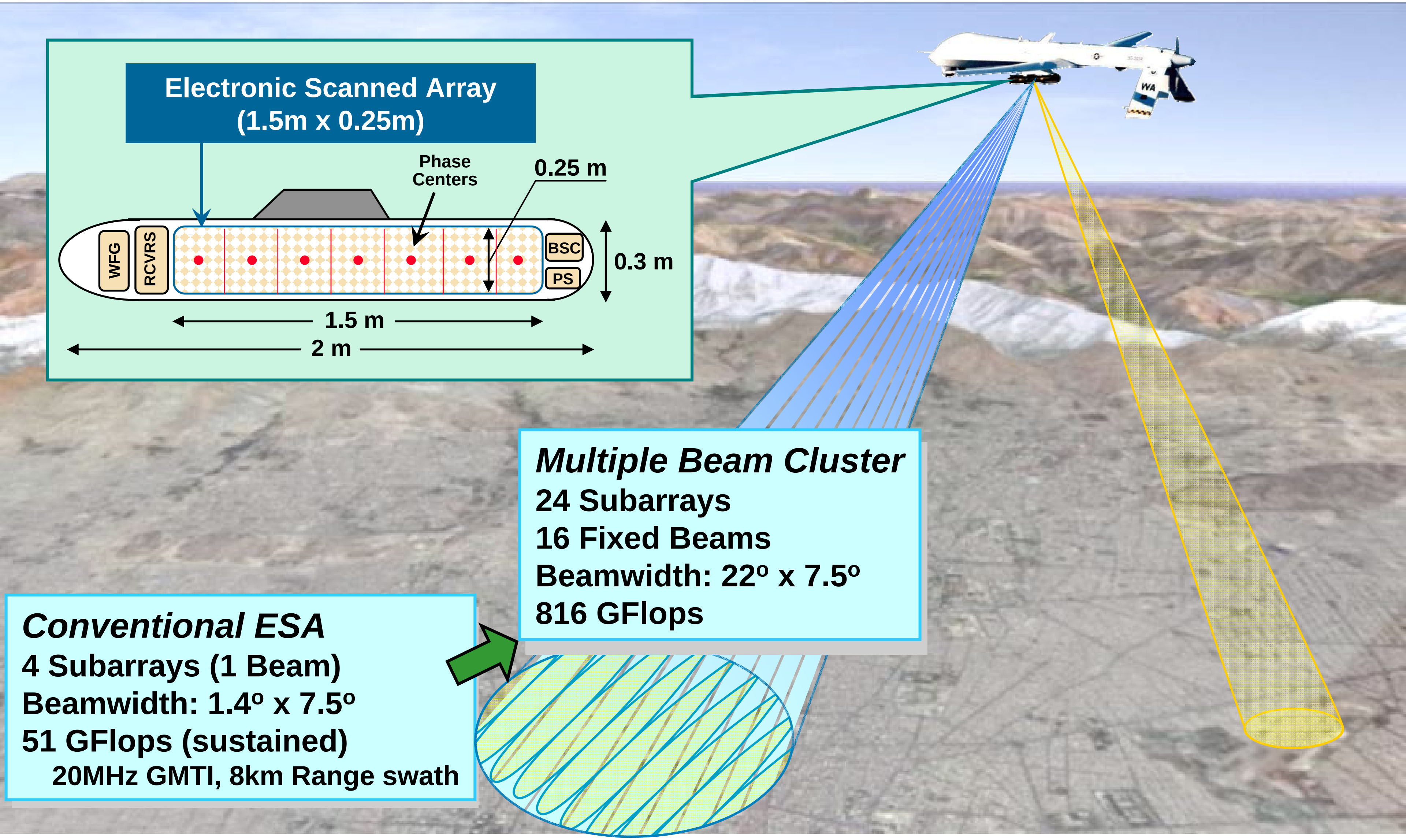
4 Subarrays (1 Beam)

Beamwidth: 1.4º x 7.5º

51 GFlops (sustained)

20MHz GMTI, 8km Range swath

X-Band Pod Radar Example



Multiple Beam Cluster

24 Subarrays

16 Fixed Beams

Beamwidth: 22º x 7.5º

816 GFlops

Conventional ESA

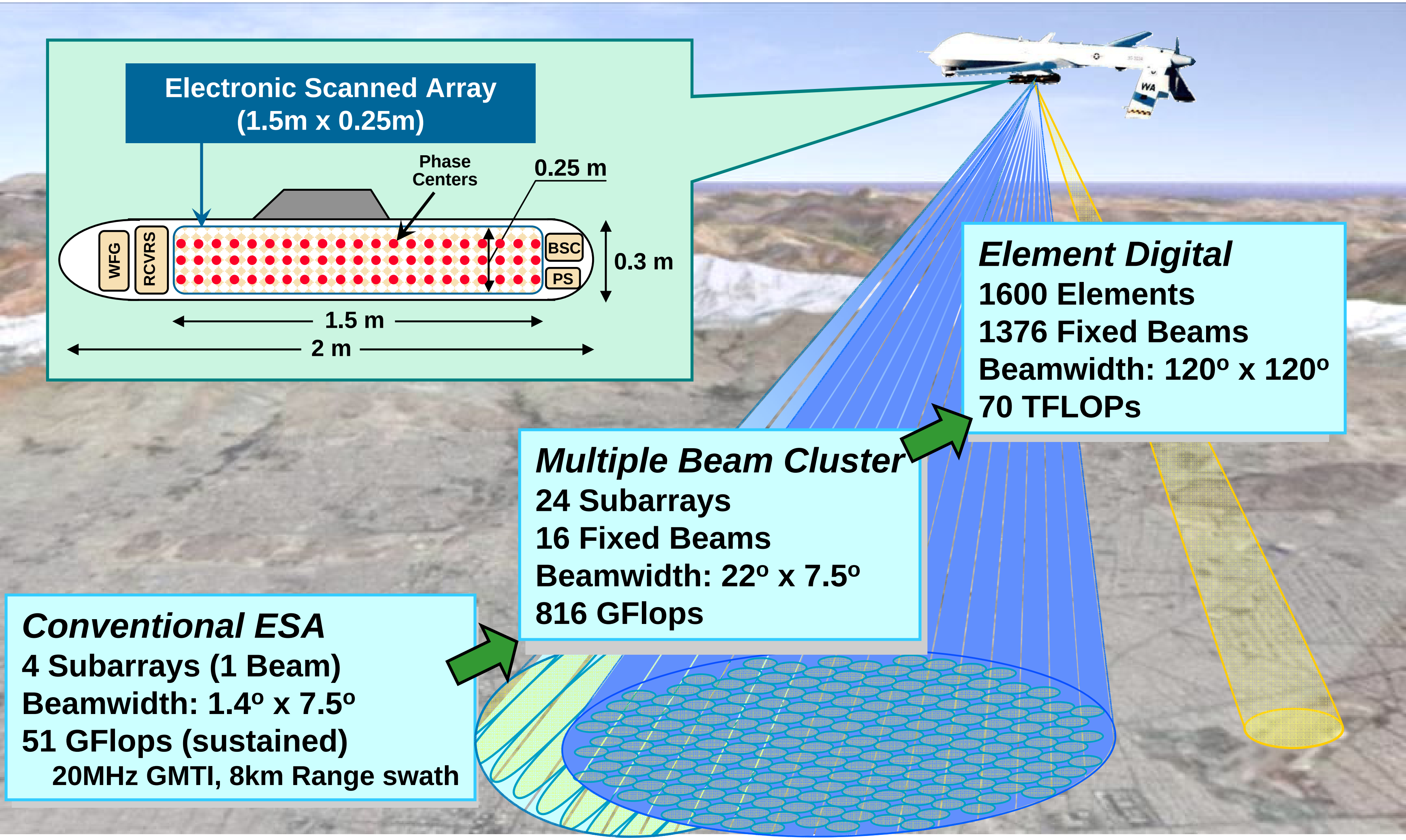
4 Subarrays (1 Beam)

Beamwidth: 1.4º x 7.5º

51 GFlops (sustained)

20MHz GMTI, 8km Range swath

X-Band Pod Radar Example



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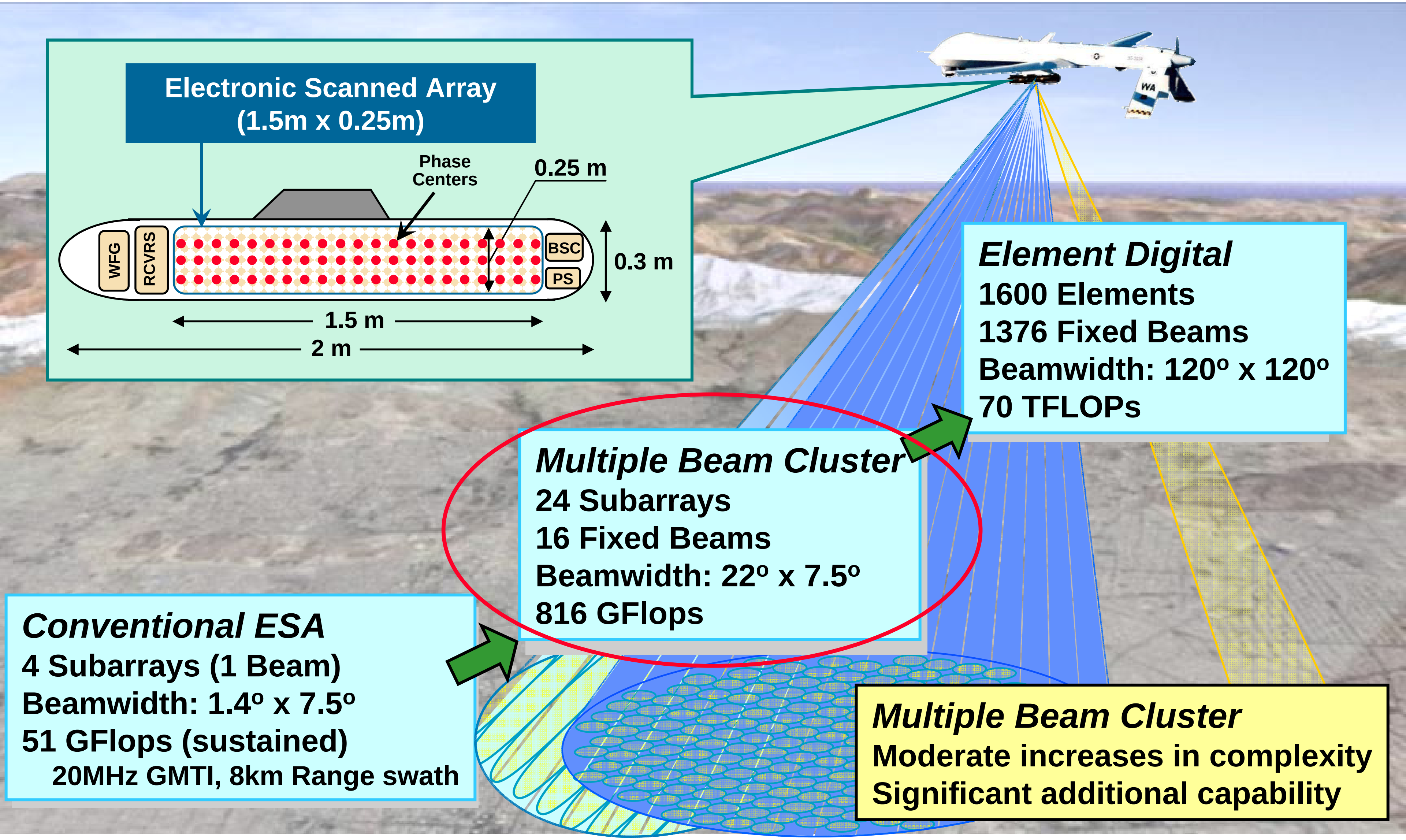
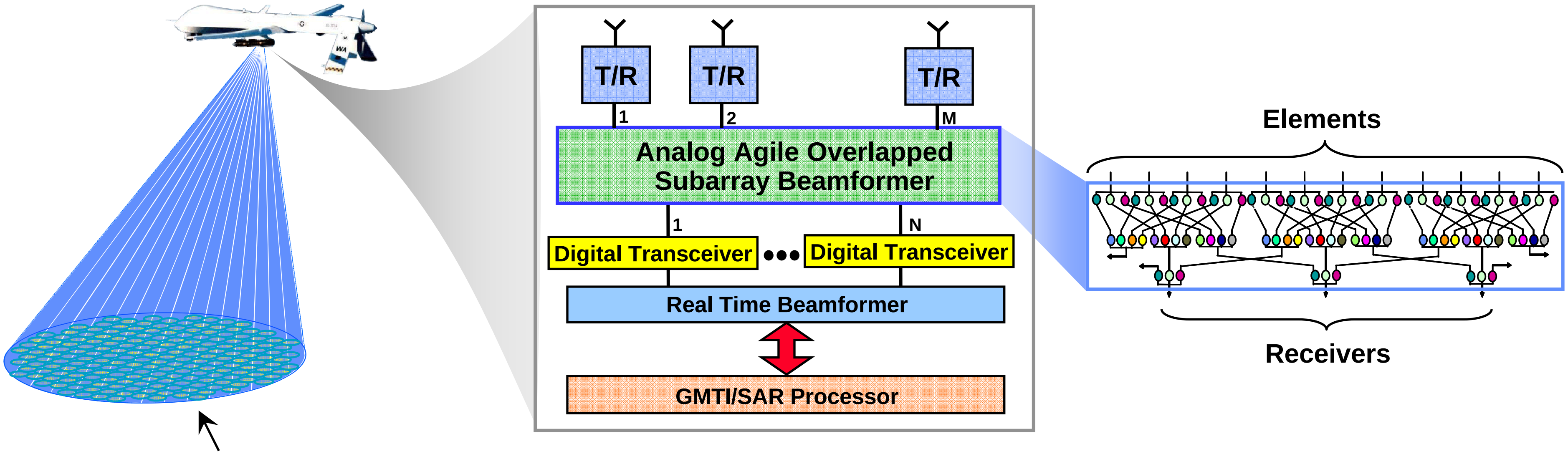


Outline

- **Overlapped subarray overview**
- RFIC measurements
- Pattern predictions
- Summary

Multifunction Array Concept



Multiple Beam Cluster

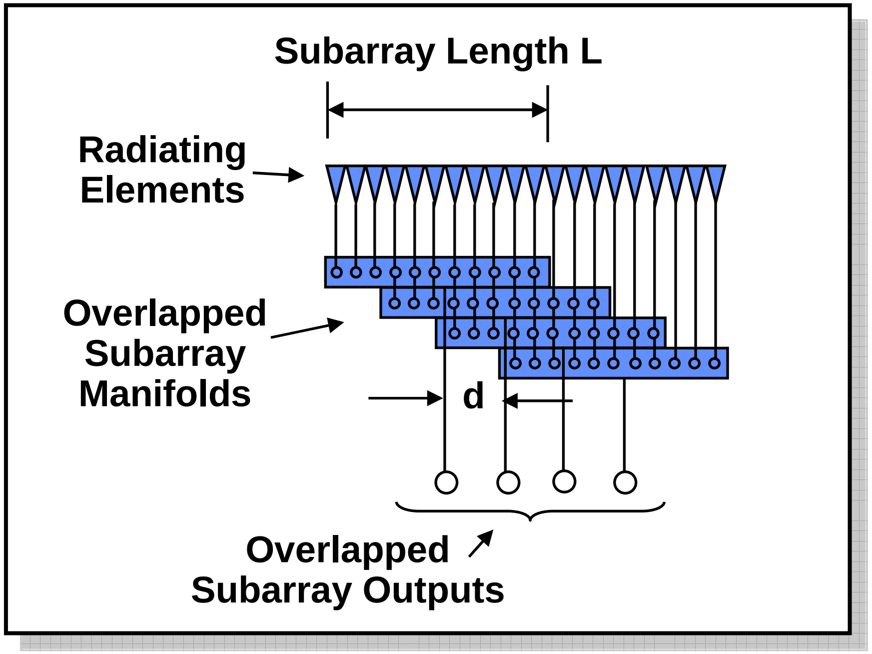
Multifunction Array Architecture

Overlapped Subarray Beamformer

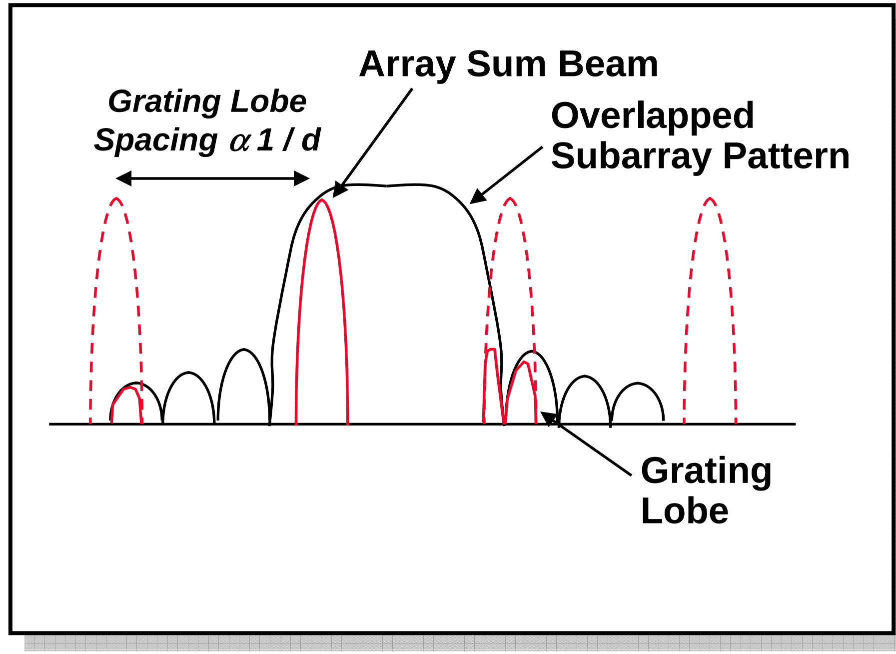
- **Multiple beam clusters enable new capabilities for RF sensors**
  - Increased coverage rate
  - Efficient time power management
  - Multiple simultaneous modes
- **Conventional overlapped subarray beamformer is a significant cost driver**

Overlapped Subarray Concept

Array Aperture



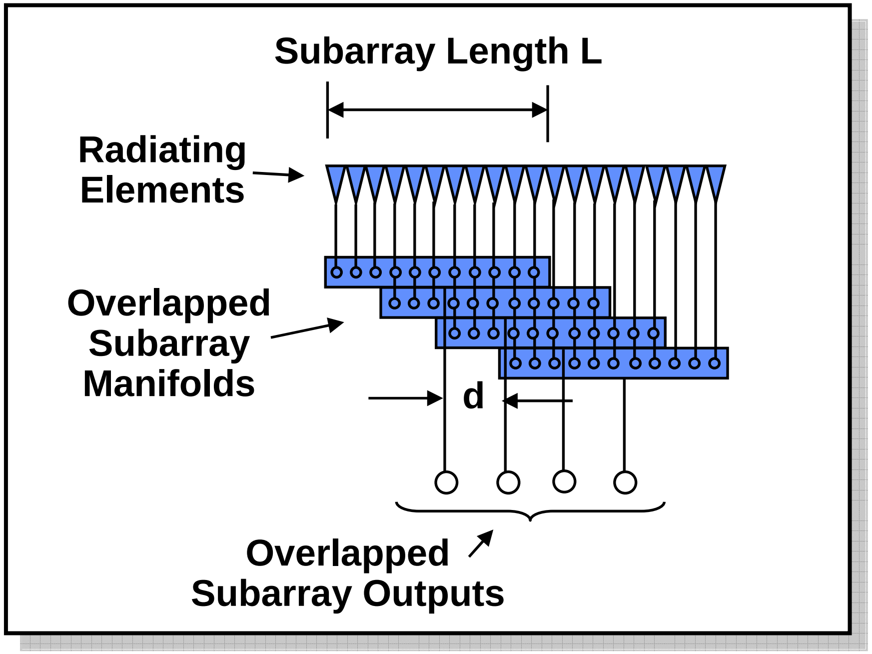
Far Field Pattern



- **Overlapped subarray achieves minimum number of controls required for a given scan volume**
- **Can be used to form multiple digital beam clusters**

Overlapped Subarray Concept

Array Aperture



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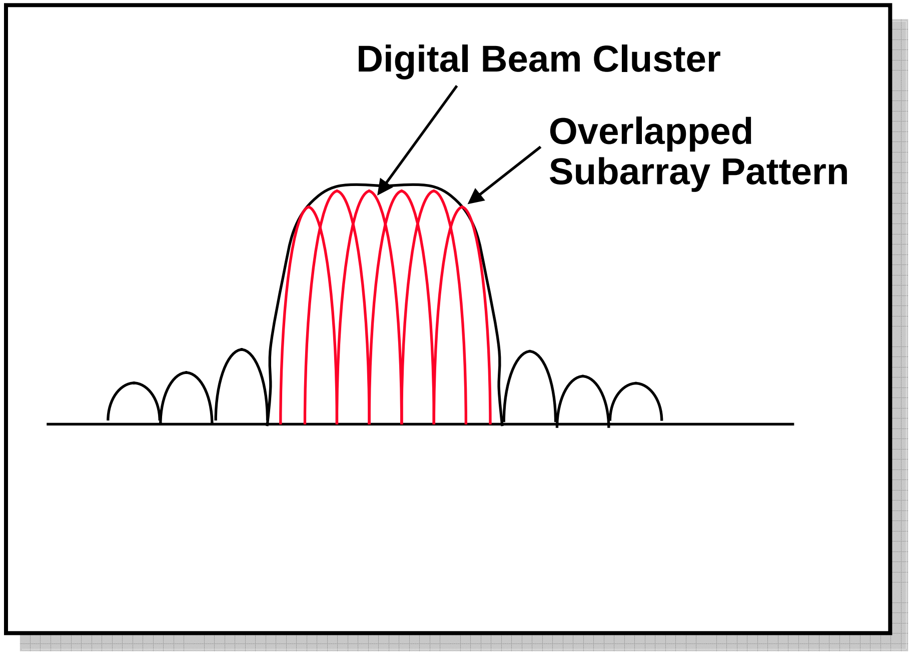

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Overlapped Subarray Concept

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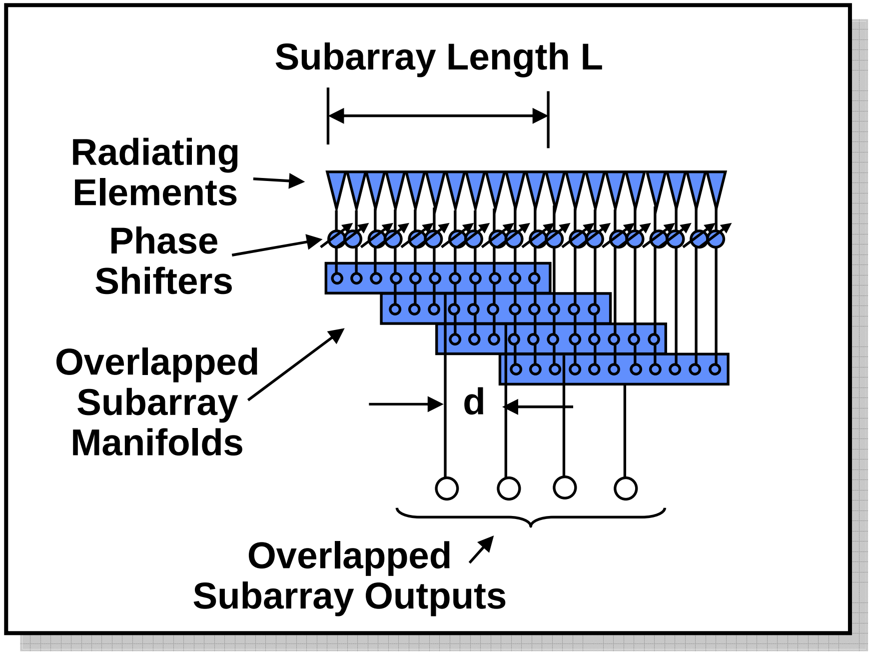
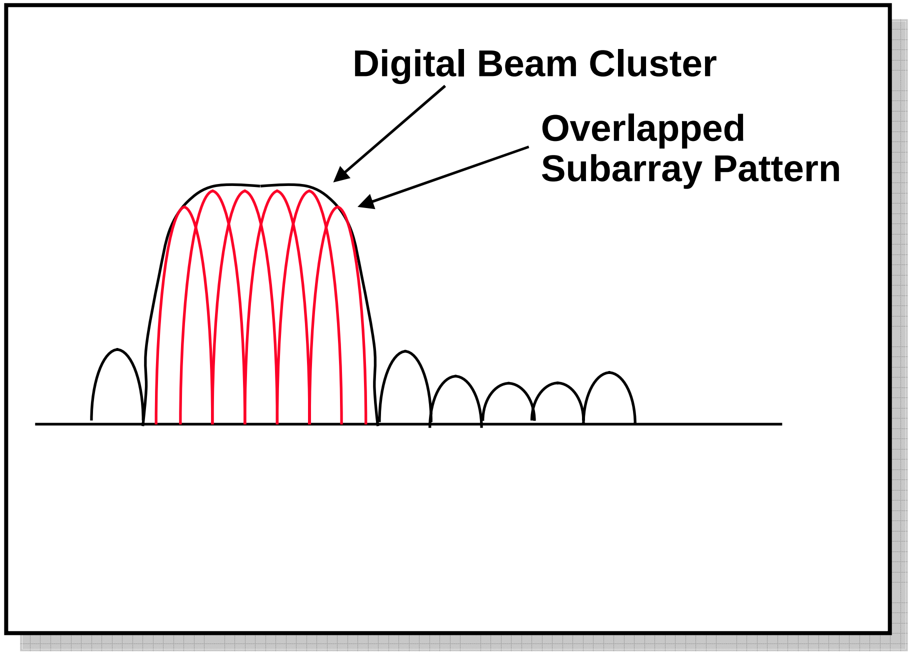


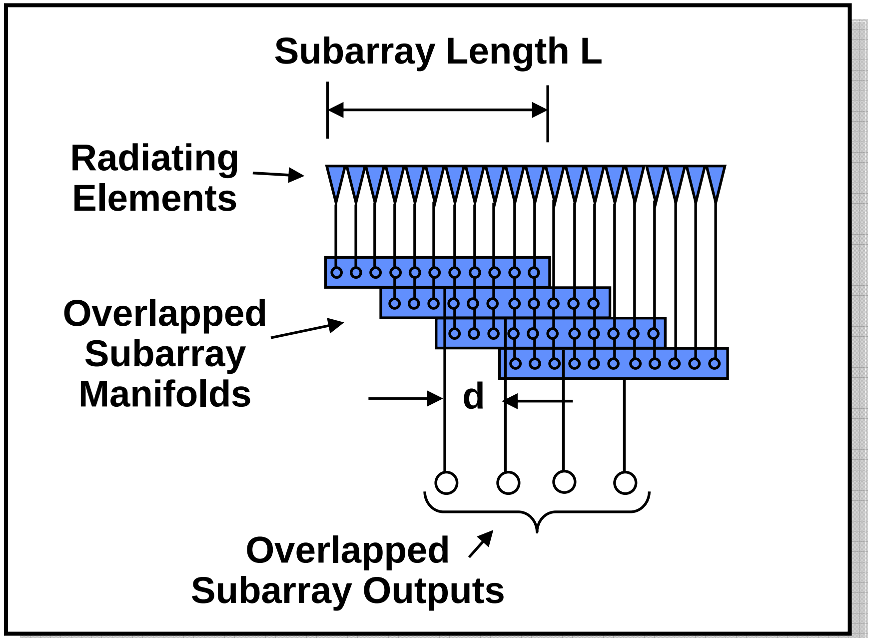
Far Field Pattern



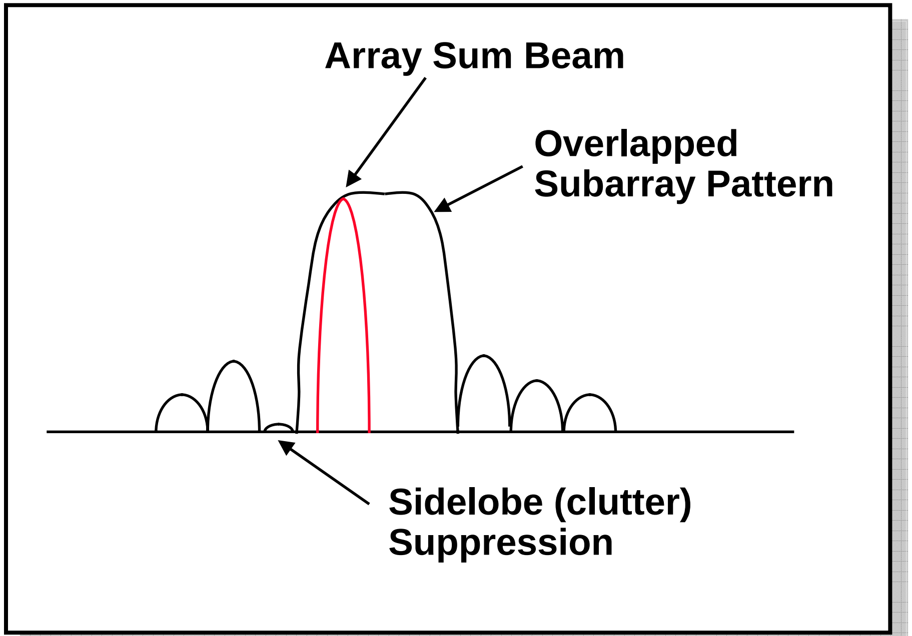
- Overlapped subarray achieves minimum number of controls required for a given scan volume
- Can be used to form multiple digital beam clusters
- Phase shifters at each element scans subarray pattern

RFIC Overlapped Subarray

Array Aperture

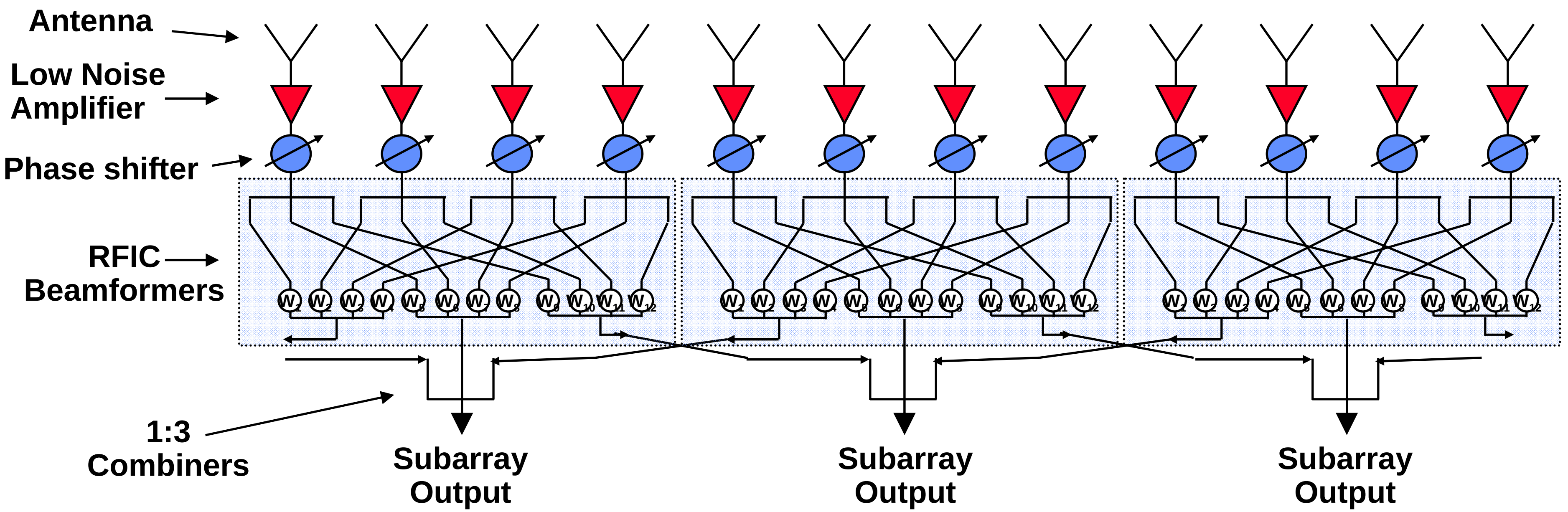


Far Field Pattern



- **Overlapped subarray achieves minimum number of controls required for a given scan volume**
- **RFIC used to form sidelobe nulls in subarray pattern**

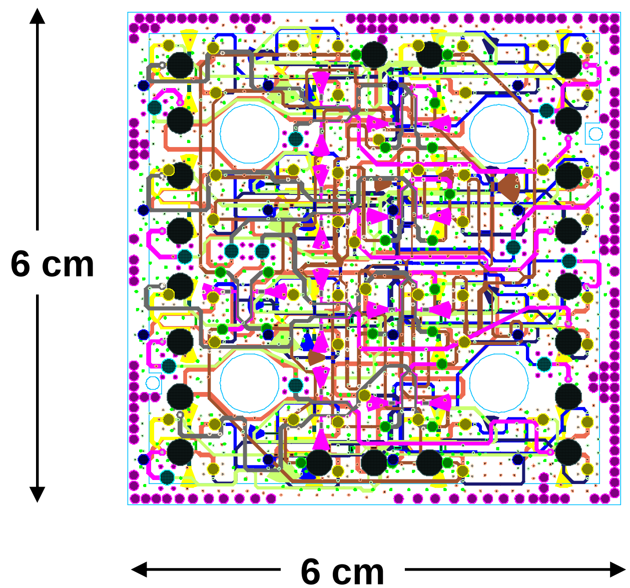
1D Overlapped Subarray Architecture



- **12 element overlapped subarray architecture**
  - Component redundancy simplifies design
  - 3 to 1 overlapping
  - Weights are adjustable in RFIC implementation (pattern control)
  - Weights can be used to compensate for manufacturing errors

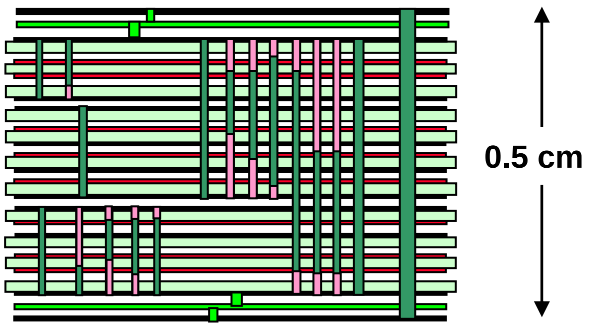
Previous Work –
Passive Overlapped Subarray Manifold

Multilayer Overlapped Subarray

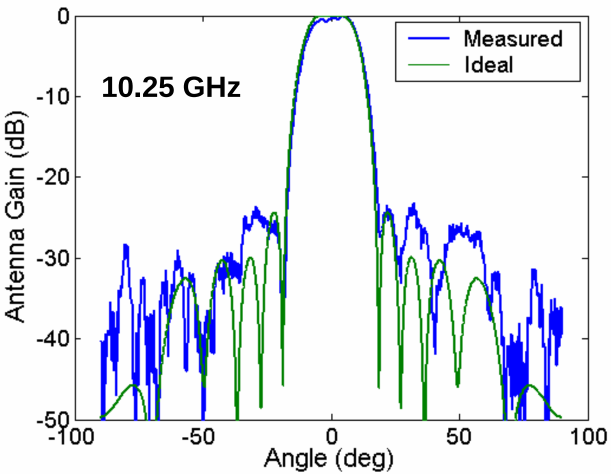


- Multilayer stripline board
- Custom MIT LL design
- In-house assembly and testing

Manifold Stackup



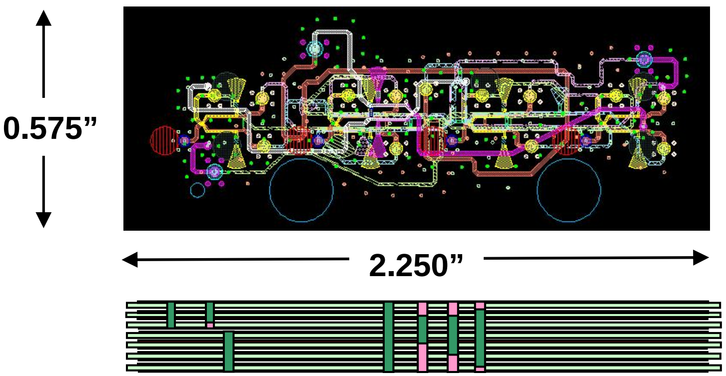
Overlapped Subarray Pattern



J.S. Herd, S.M. Duffy, and H. Steyskal, "Design Considerations and Results for an Overlapped Subarray Radar Antenna", *IEEE Aerospace Conference Digest*, Big Sky, MT (March 2005).

RF Integrated Chip (RFIC) Beamforming

Current Passive Overlapped Subarray

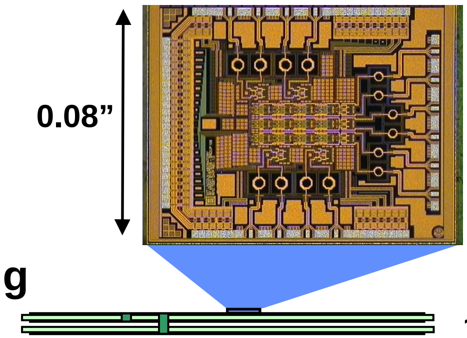


11 layer circuit board
(backdrilled vias, buried resistors)

36.5 g

RFIC Approach

6.5 g



Simple circuit board

Parameter	PCB	RFIC on PCB	Scaling
Cost	$300/element	$35/element	X 9
Mass	36.5 g	6.5 g	X 6
Volume	1 in^3	0.1 in^3	X10
DC Power	0	50-100 mW	
Dynamic Range	SFDR (1MHz) >>100 dB	SFDR (1MHz) 69 dB	
Dynamic Range after Downconversion	SFDR (1MHz) 77 dB	SFDR (1MHz) 74 dB	÷2

- **RFIC beamformer reduces cost, weight and volume**
  - Dynamic range and noise figure are within 3 dB and 0.1 dB of conventional
- **Design has overlapped subarray *and* integrated LNA on single CMOS chip**
- **Beamformer is programmable for optimal performance**

Outline

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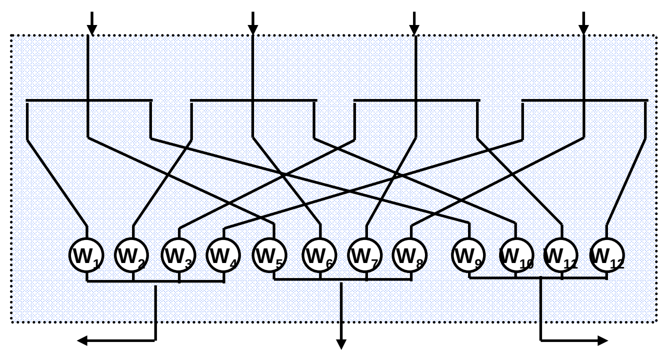
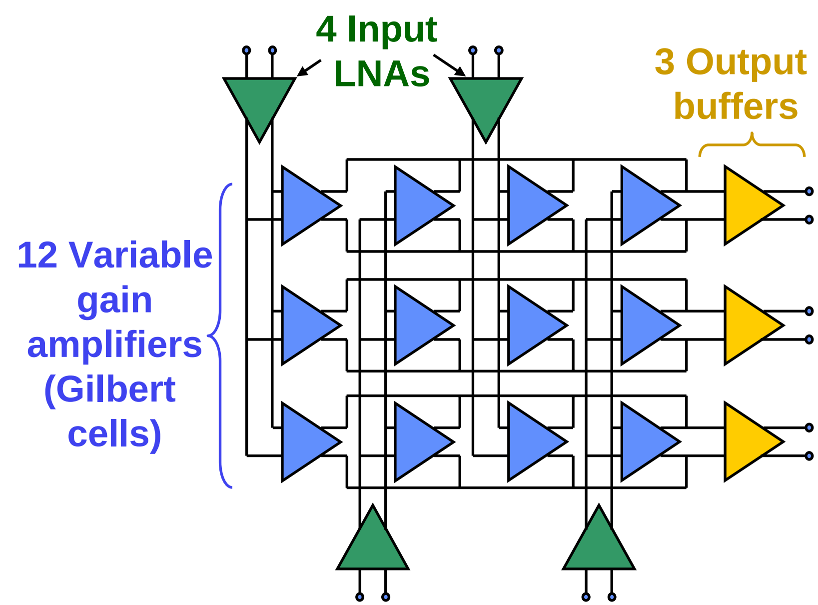
RFIC Overlapped Subarray Block Diagram

Overlapped Subarray Network



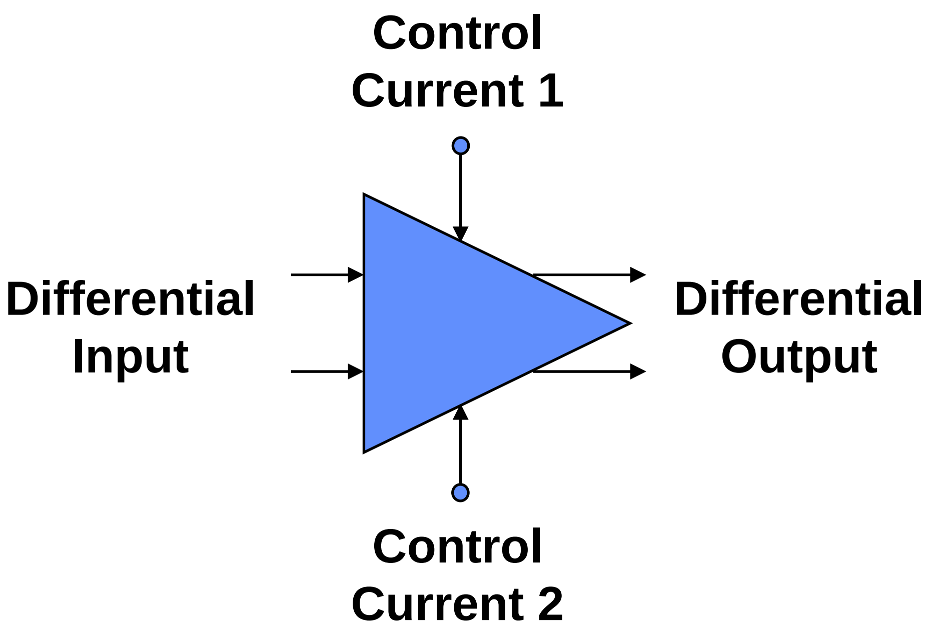
- 7 port network
- 12 independent weights

RFIC Beamformer Implementation



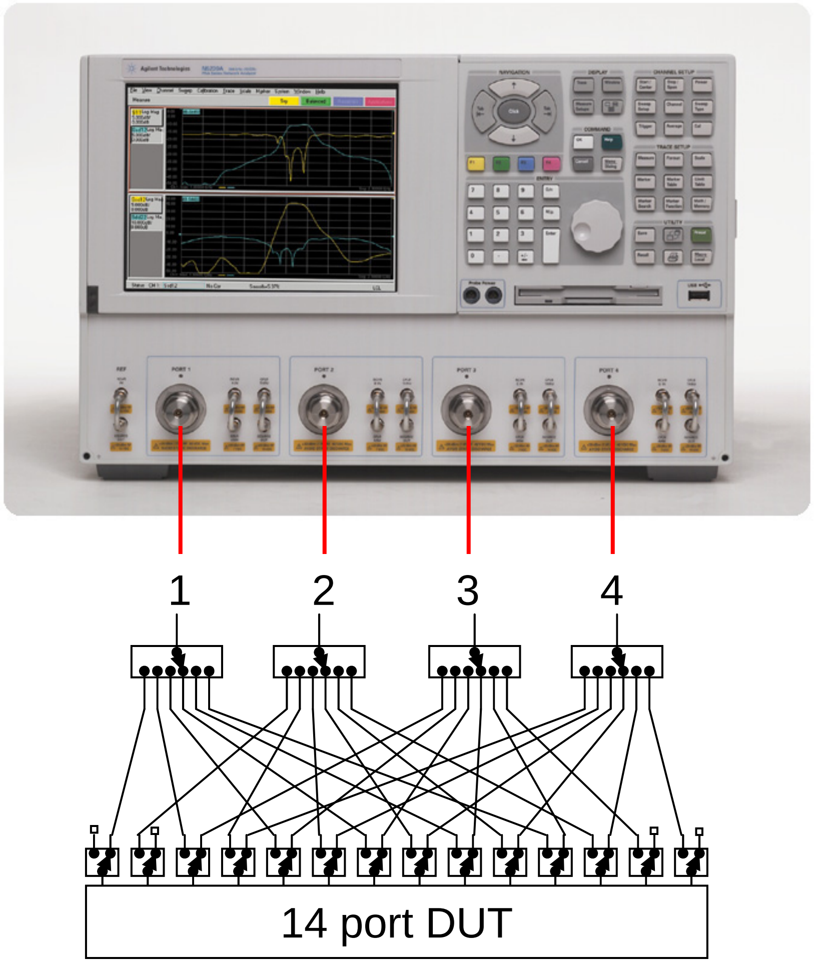
- Gilbert cell gain controlled by two control currents
- Gilbert cell also provides 180º phase adjustment

Amplitude and Phase of Variable Gain Amplifier

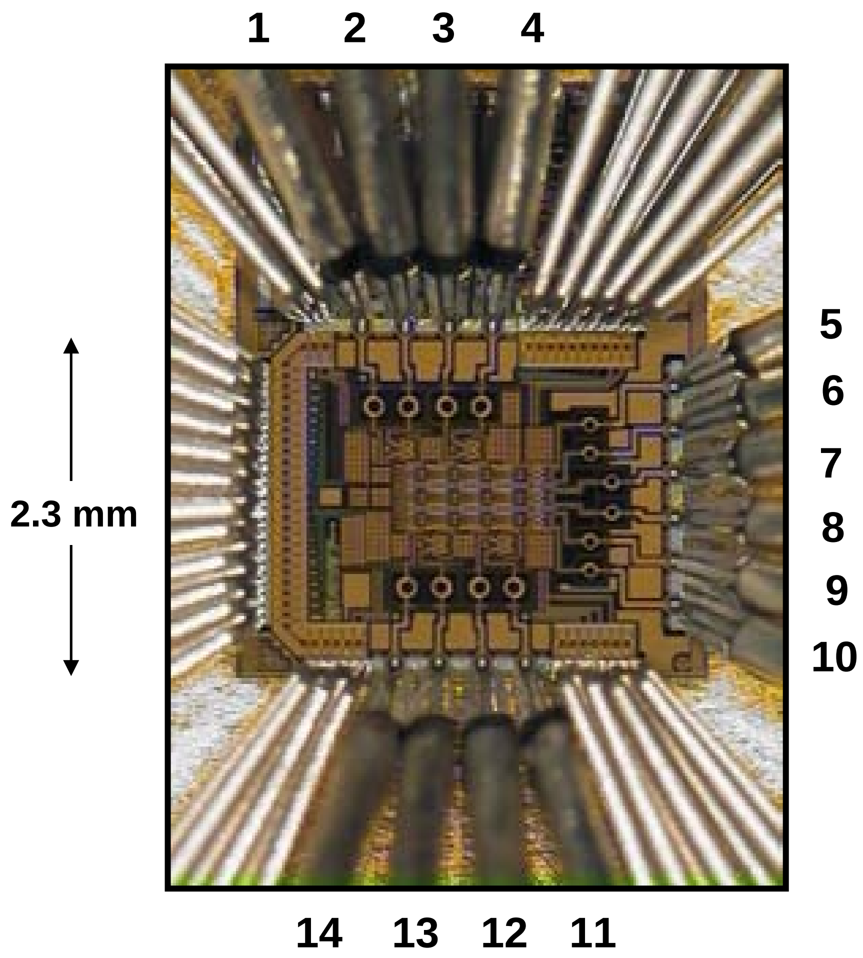


	Normalized Current	Output Amplitude Phase
Control 1 Control 2	1 0	$1\angle 0^o$
Control 1 Control 2	0 1	$1\angle 180^o$
Control 1 Control 2	0.25 0.75	$\sim 0.8\angle 180^o$
Control 1 Control 2	0 0	0

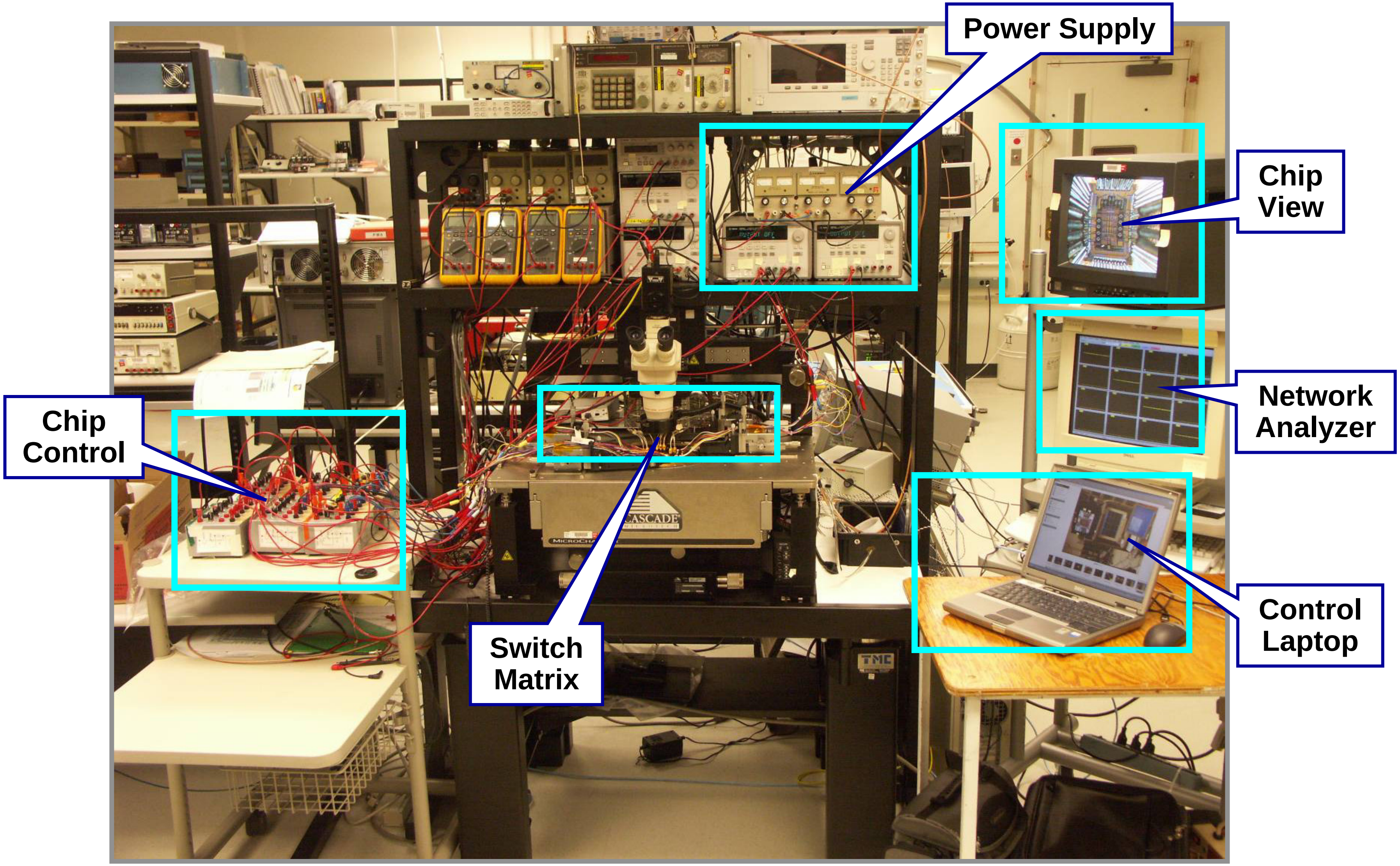
RFIC Probe Testing



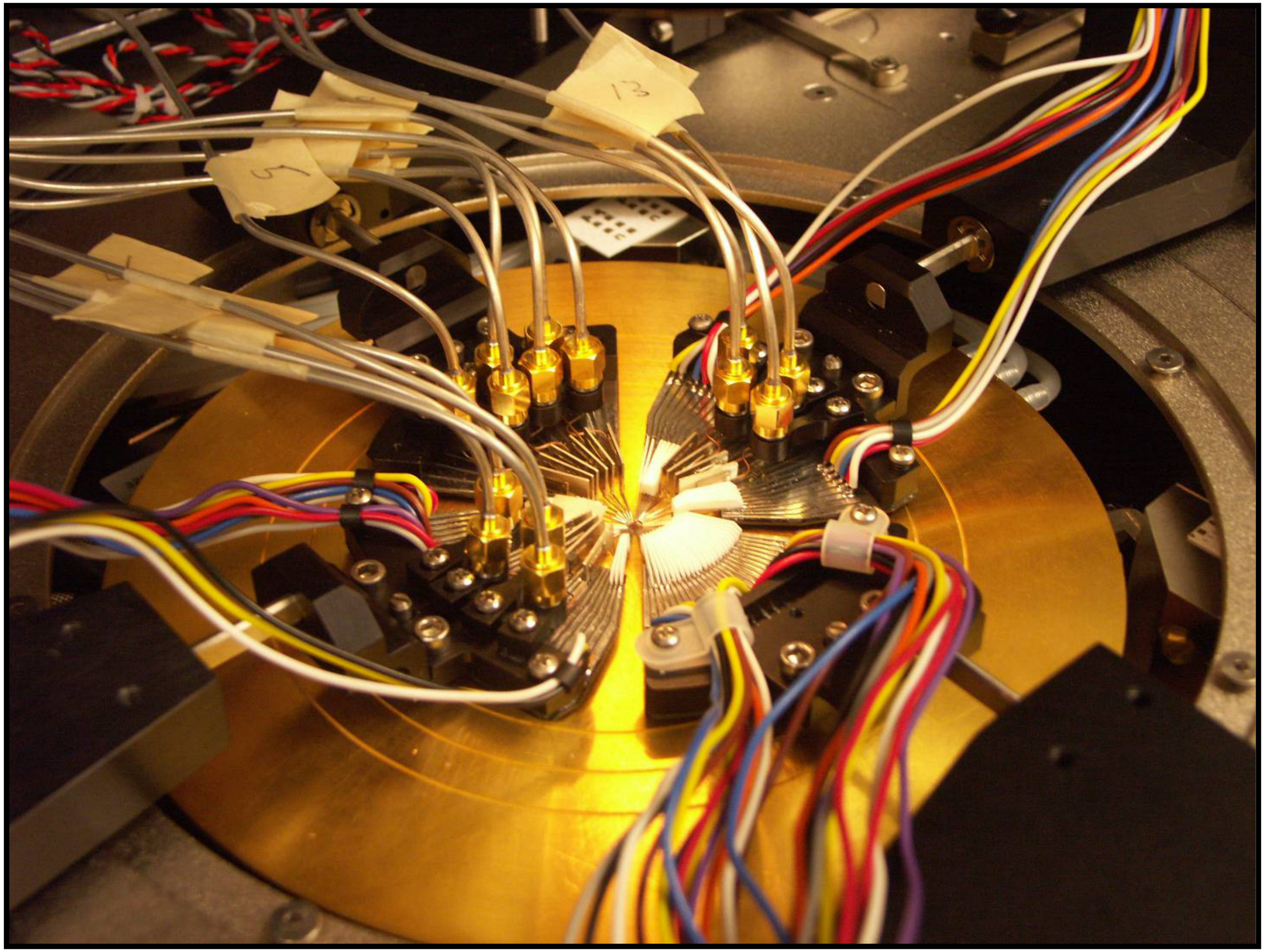
Switch Matrix



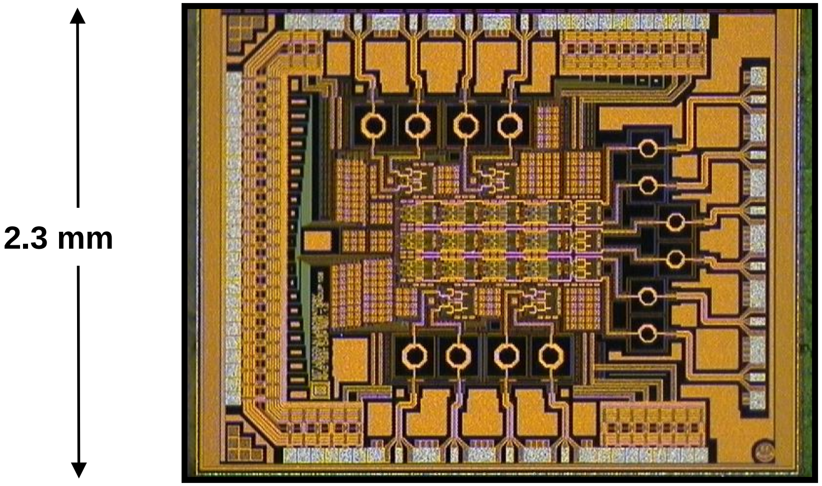
Probe Testing Measurement Setup

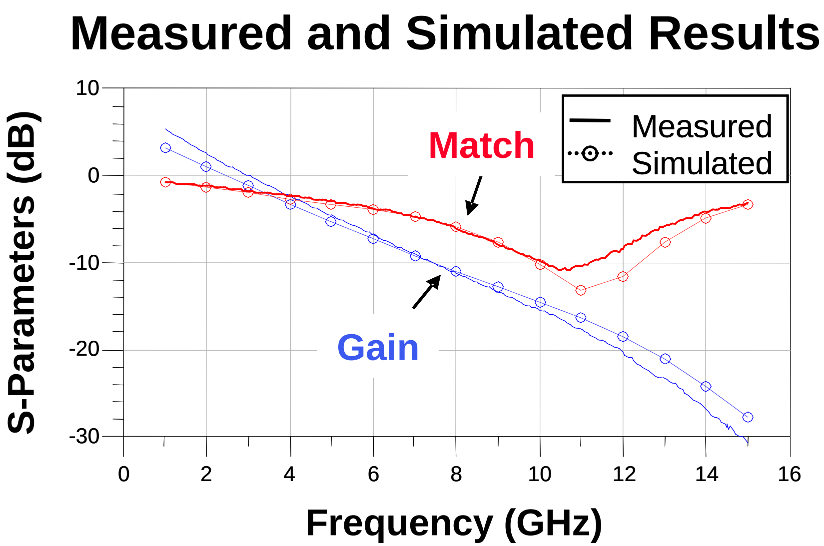


Closeup of Probes and RFIC



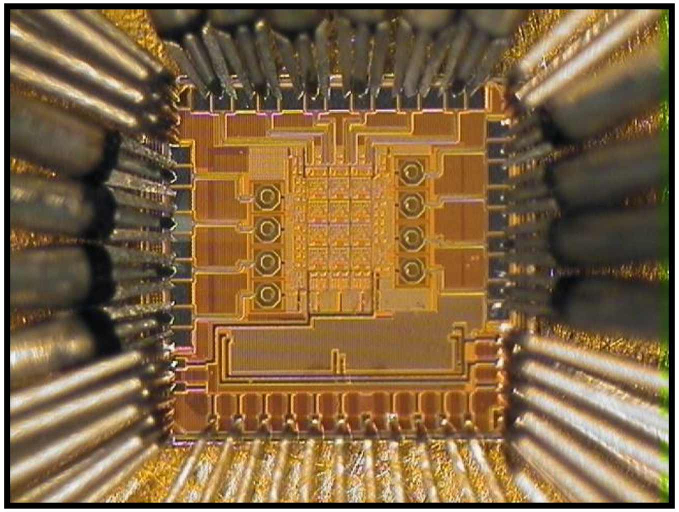
Measured Data from RFIC Test Chip

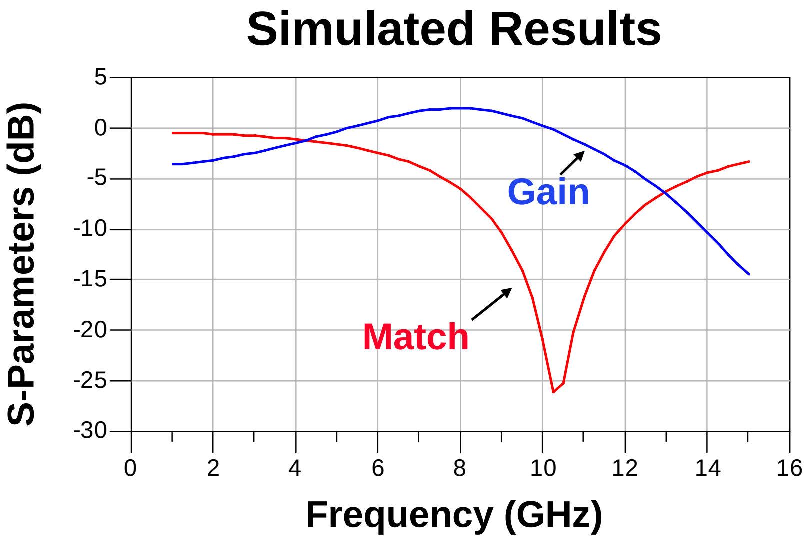




- Proof-of-concept RFIC beamformer
  - TSMC 0.18 µm RF-CMOS process
  - 284 mW (158 mA at 1.8V bias)
- Demonstrates successful implementation

Rev 2 RFIC Design





- **RFIC beamformer with integrated serial-parallel converter and LNA**
  - **IBM 0.13 µm RF-CMOS process**
  - **156 mW (120 mA at 1.3V bias {RF section})**
  - **Predicted noise figure ~ 3.6 dB**
- **Fully integrated RF front-end**

Outline

- Overlapped subarray overview
- RFIC measurements
- **Pattern predictions**
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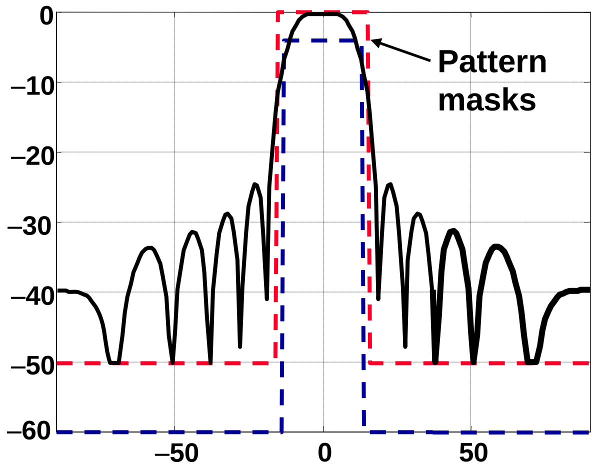
Beam Pattern Agility

- **Gain control of RFIC beamformer provides pattern agility**
  - **Dynamically control subarray pattern**
    - **Fixed weights**
    - **Adaptive control**

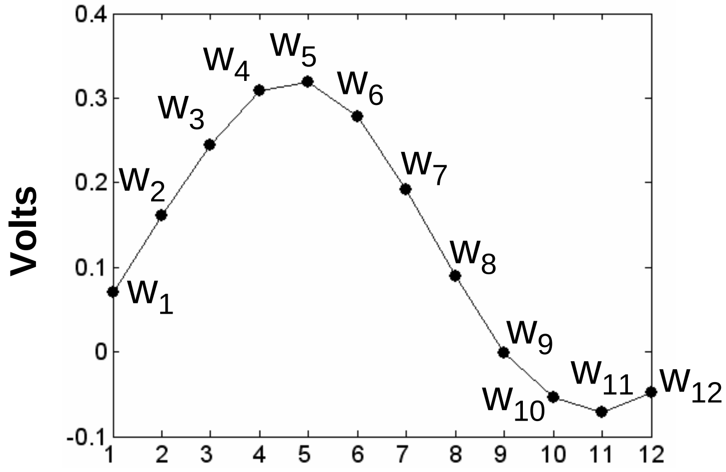
- **Pattern synthesis – desirable fixed weight patterns**
  - **Sector beams**
    - **Alternate projections method**
    - **Convex optimization method**
  - **Common beam patterns**
    - **Uniform illumination (maximum gain)**
    - **Monopulse**

Alternating Projections Design – Low Average Sidelobes

Optimized Pattern



Weighting Coefficients

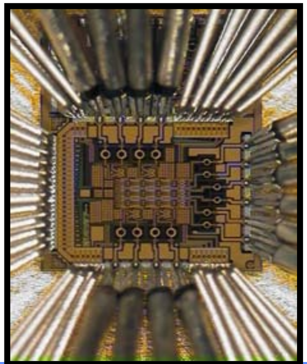


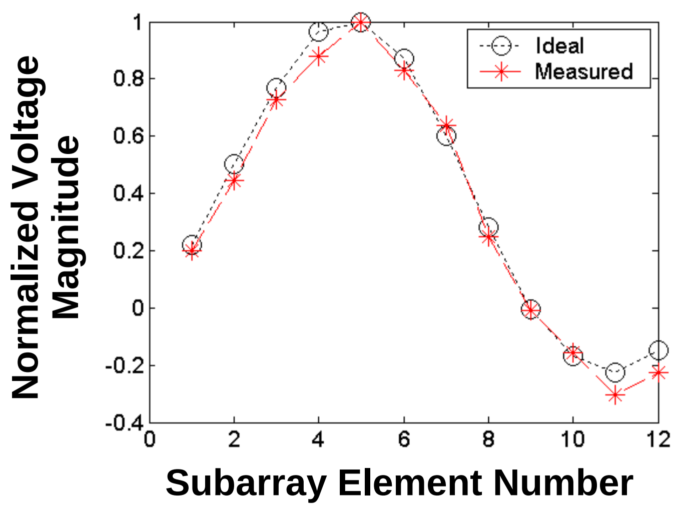
- **Optimal overlapped subarray design**
  - **Best pattern obtained by -50 dB max sidelobe mask**
  - **Weighting coefficients are asymmetric due to power pattern synthesis**

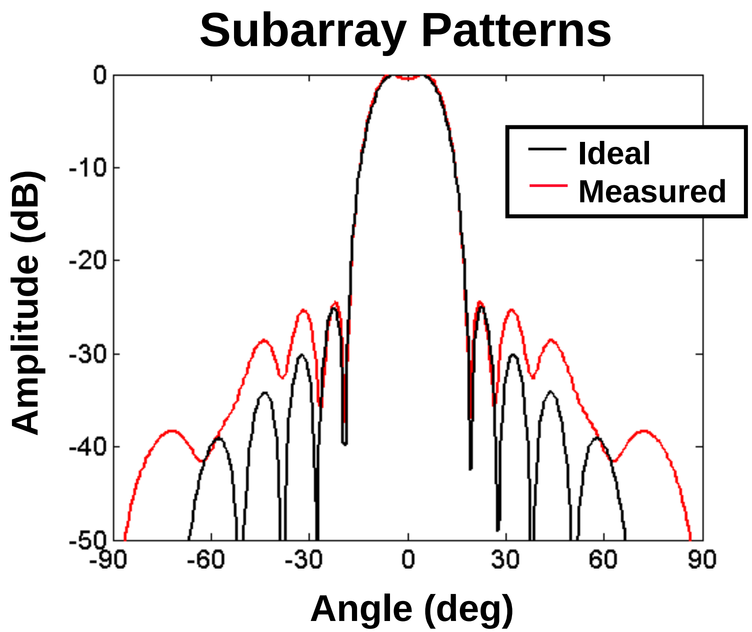
J.S. Herd, S.M. Duffy, and H. Steyskal, "Design Considerations and Results for an Overlapped Subarray Radar Antenna", *IEEE Aerospace Conference Digest*, Big Sky, MT (March 2005).

Sector Beam Pattern Measurements – Low Average Sidelobes

Measurements







- **Adjust variable gain amp settings to arrive at desired low average sidelobe weighting function**

Convex Optimization – Maximum Beamwidth

- Spectral Factorization (FIR)
- Quasi-convex formulation
  - A series of convex problems
- Solved by bisection as a series of feasibility problems
- Stopband attenuation is 25dB
- Passband ripple is 2 dB

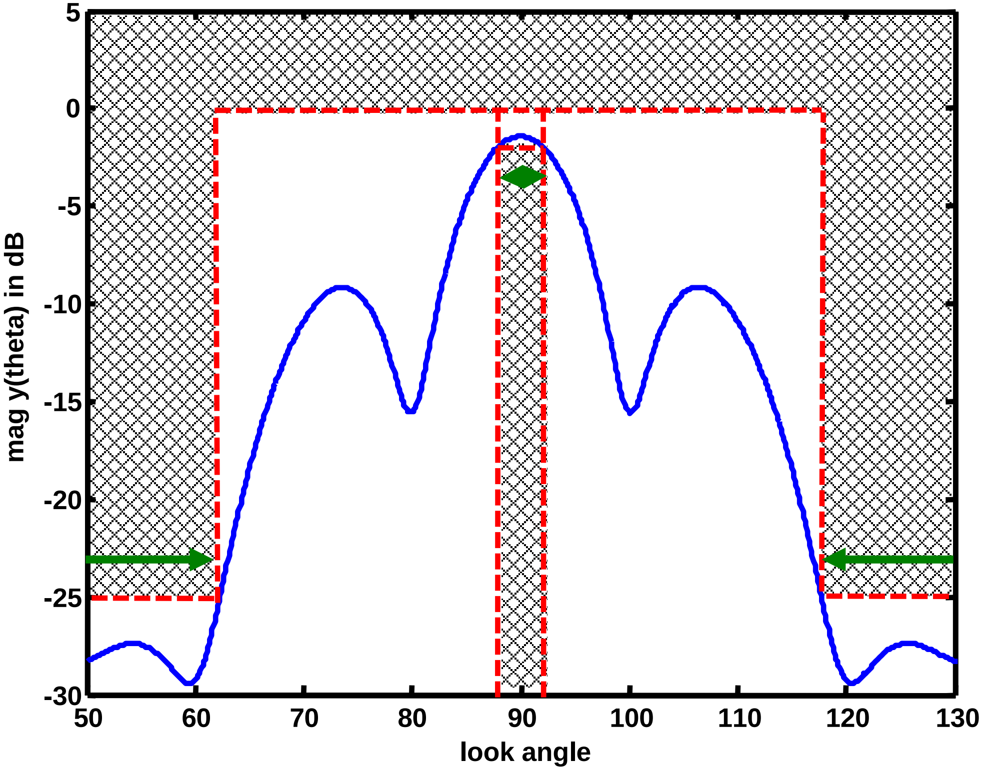
```
while( bounds < desired accuracy )

        minimize       1
        subject to:    A_si^T * r <= upper bound
                       A_pj^T * r >= lower bound

   if (the problem was feasible) lower the upper bound
   if (the problem was infeasible) raise the lower bound

end
```

$$\begin{array}{ll} \text{minimize} & 1 \\ \text{subject to:} & A_{si}^T * r \leq \text{upper bound} \\ & A_{pj}^T * r \geq \text{lower bound} \end{array}$$



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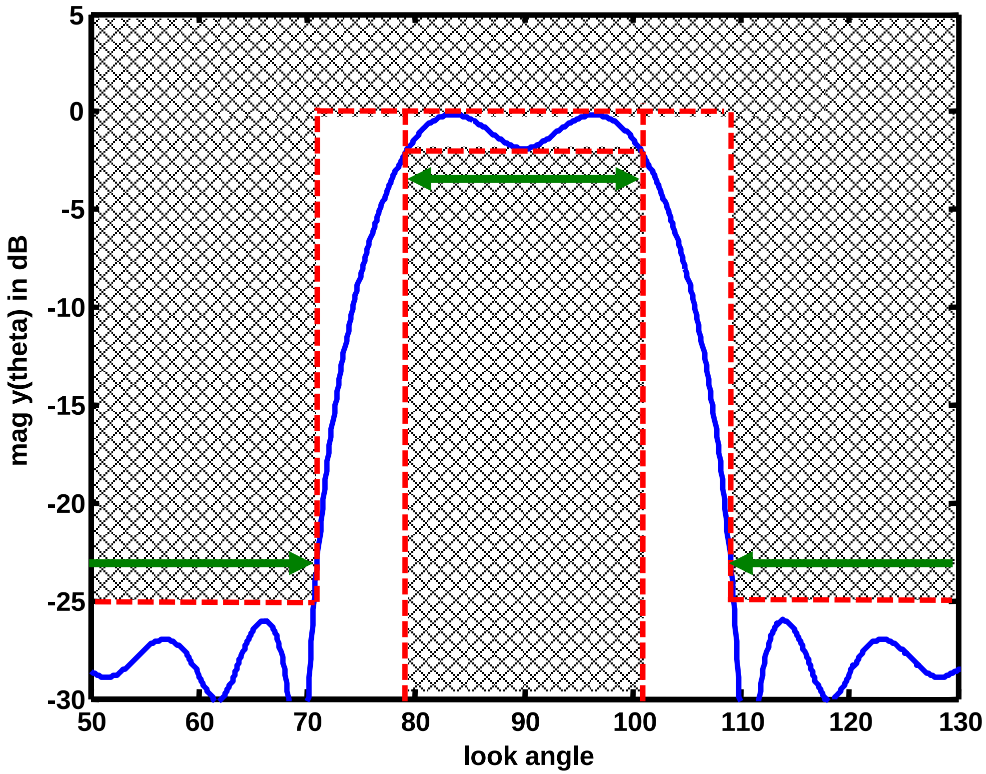
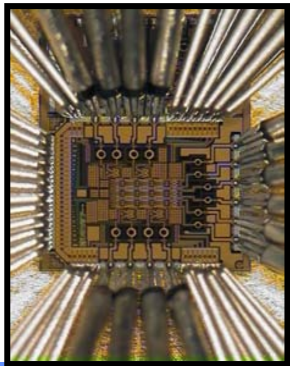
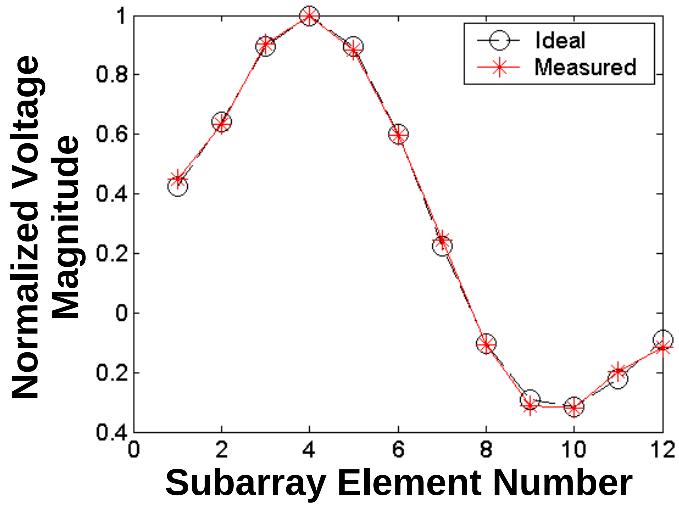
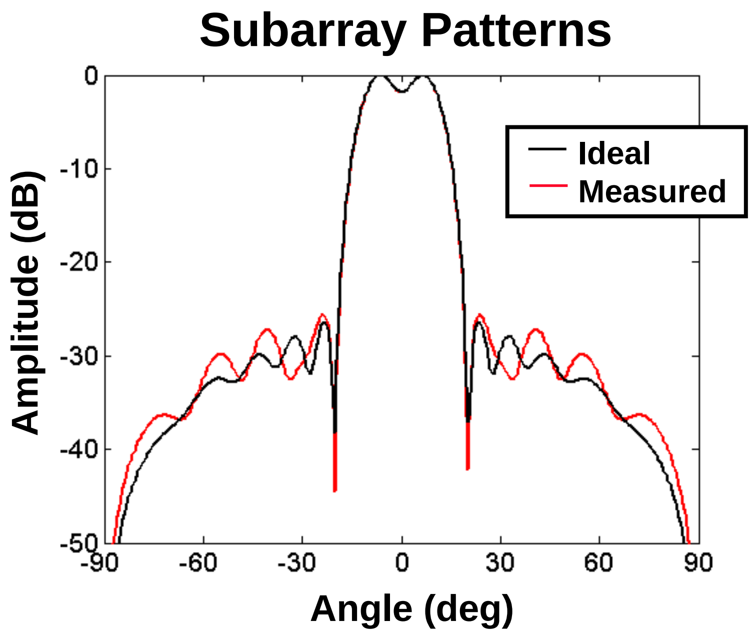


Sector Beam Pattern Measurement –
Maximum Beamwidth

Measurements



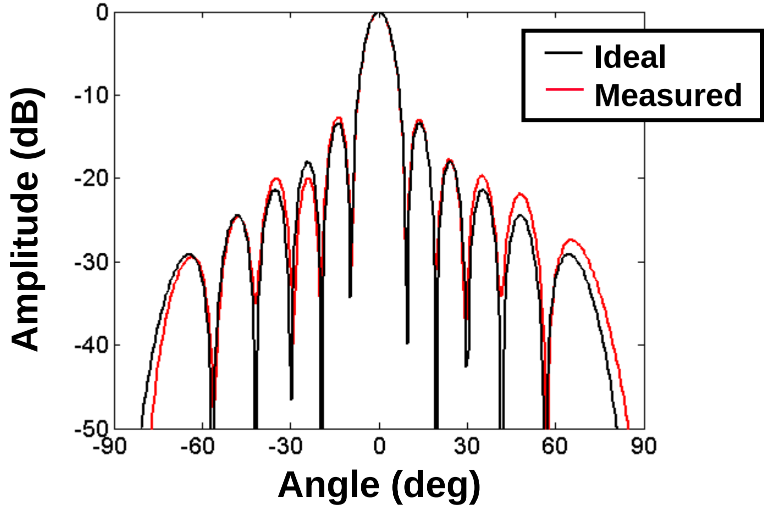


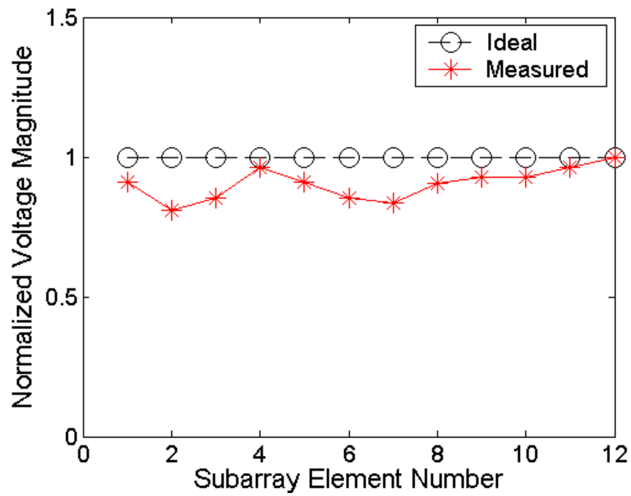


- **Adjust variable gain amp settings to arrive at desired maximum beamwidth weighting function**

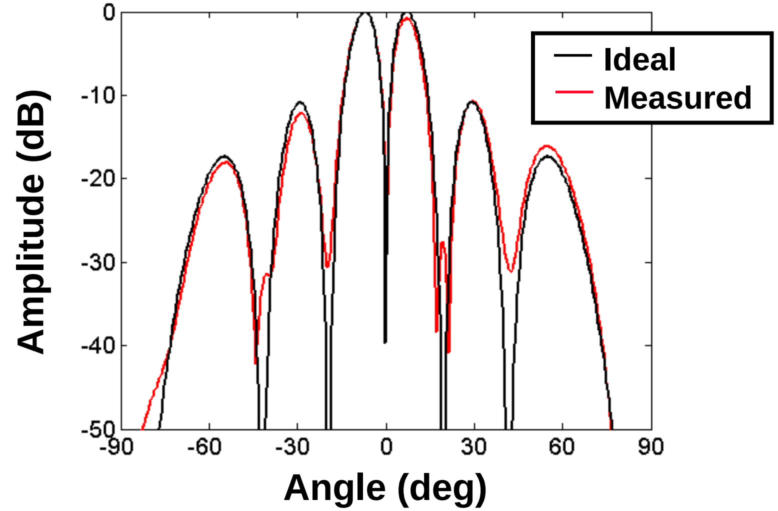
Uniform and Monopulse Beam Patterns

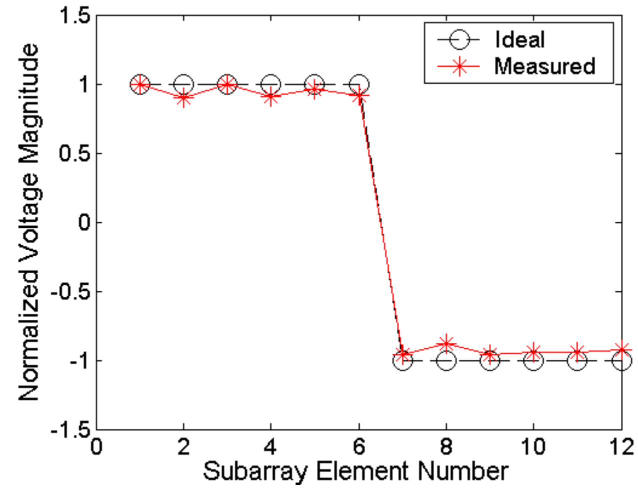
Uniform Illumination



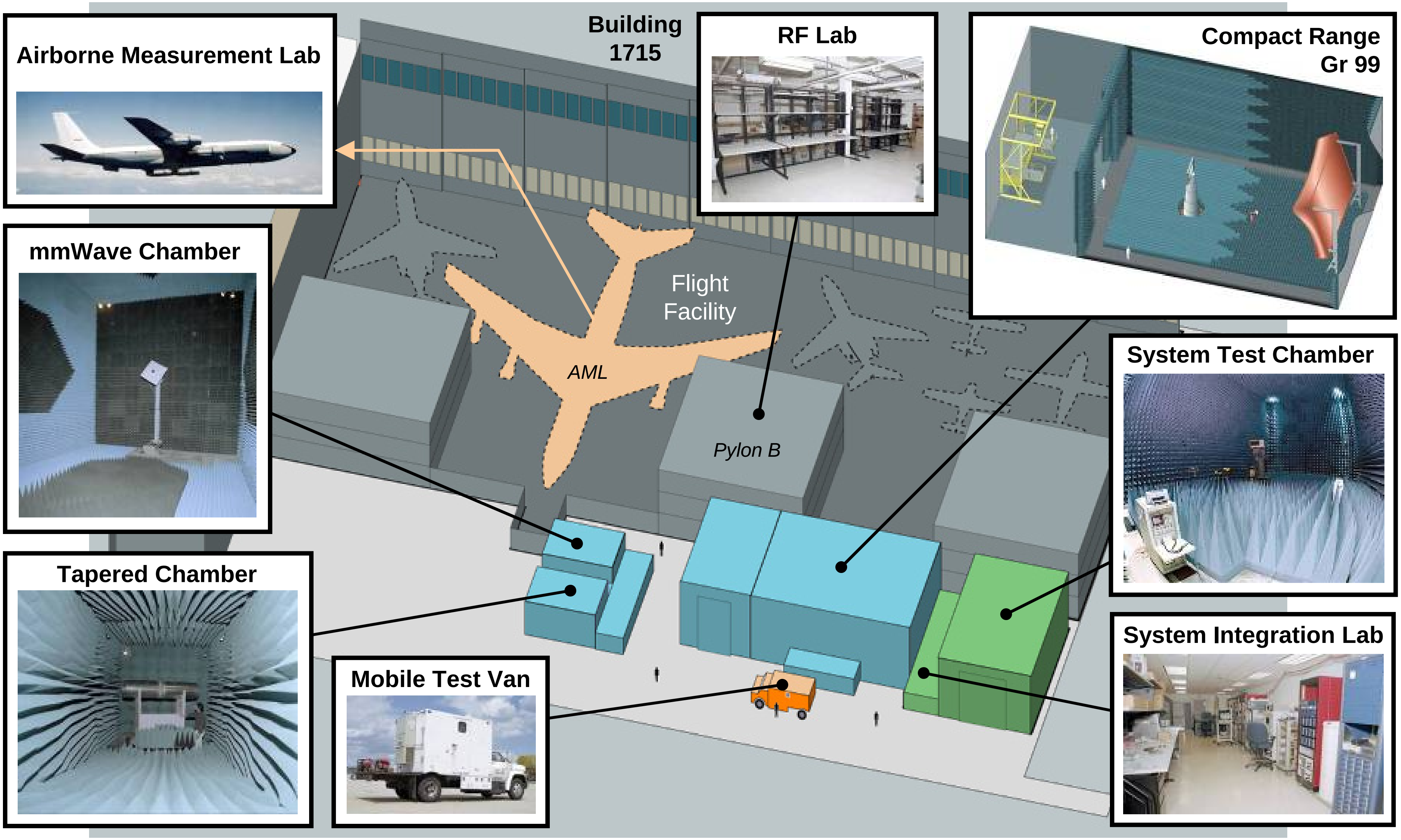


Monopulse Illumination





RF System Test Facility (RFSTF)



Summary

- Demonstrated first RFIC implementation of overlapped subarray
- RFIC beamformer has significant advantages for ESA radar
  - Highly integrated T/R module – lowers cost
  - Reduced beamformer board complexity – lowers cost
  - Agile beams – more capability
- Measured pattern weights demonstrate beam agility