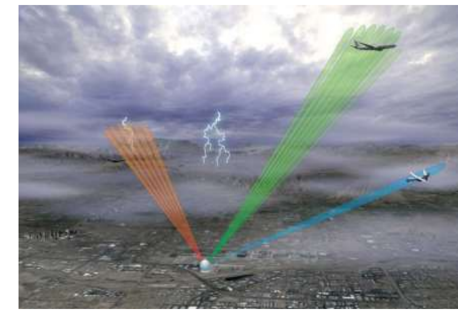
Signal Processing Challenges for Phased-Array Radar Meteorology

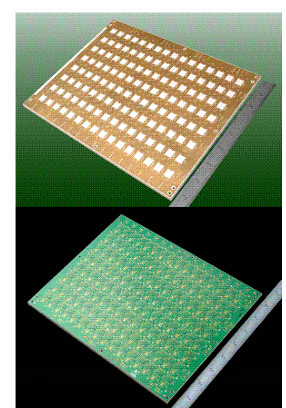
Toulouse France
24-29 June 2012

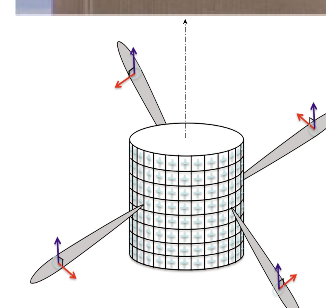


Stephen J. Frasier

Microwave Remote Sensing Laboratory
University of Massachusetts
Amherst, MA 01003

ERAD 2012



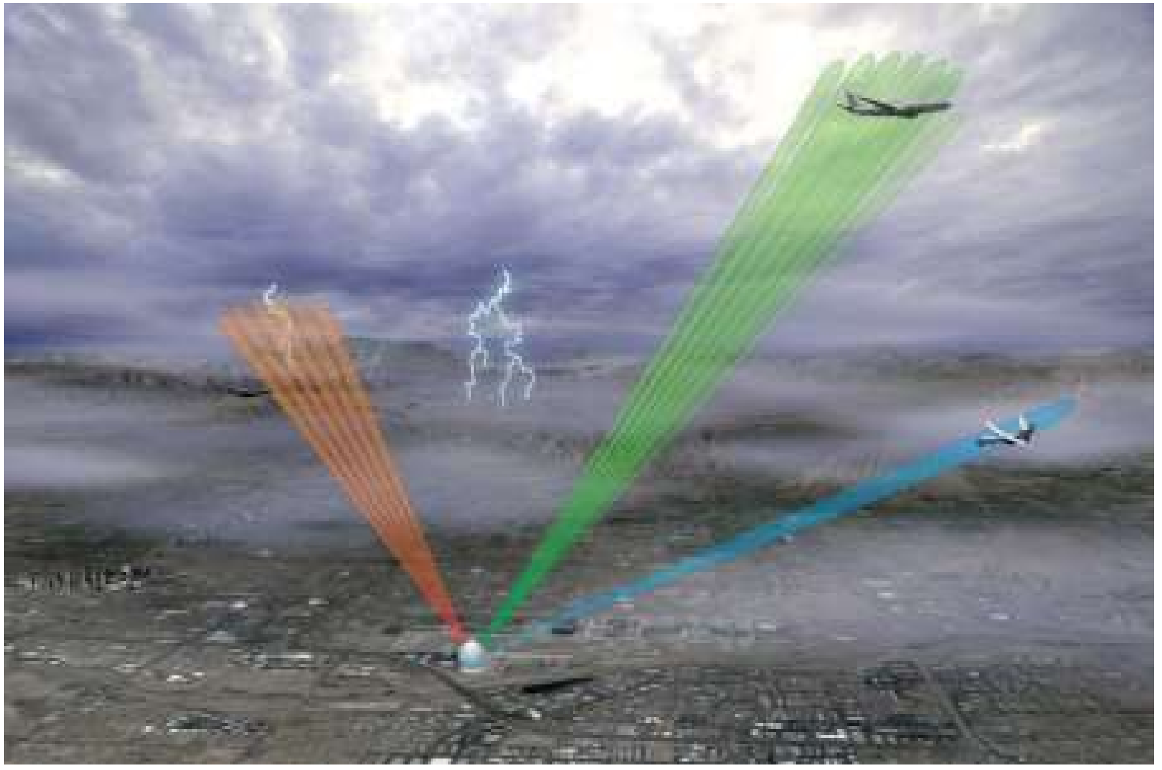


Outline

- Motivation for Phased-Arrays
- Fundamentals
- Several Examples
- Issues for Radar Meteorology
  - Rapid scanning
  - Calibration
  - Polarization
- Outlook

Why Phased Arrays?

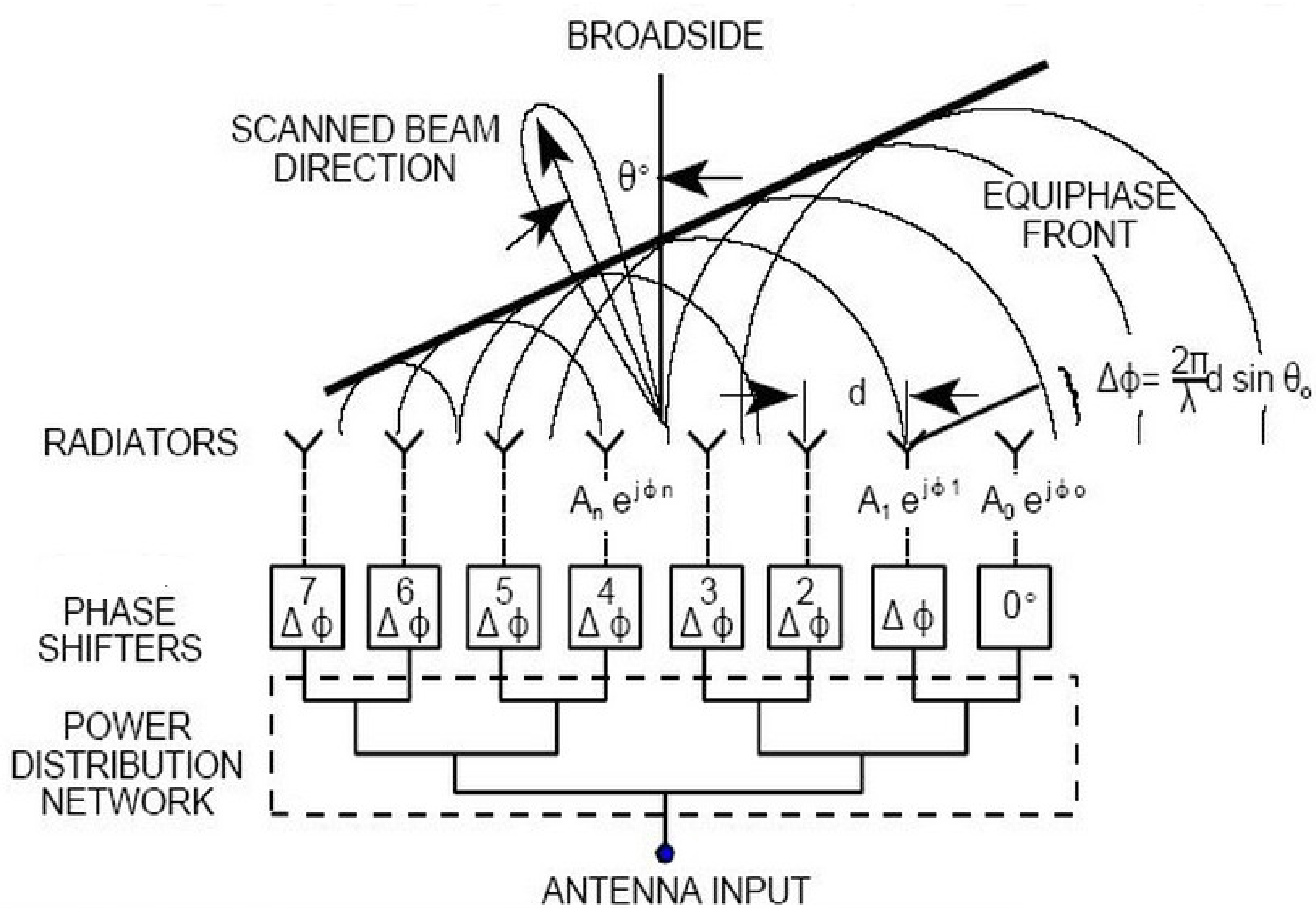
- Inertia-less scanning
- Multiple (simultaneous) beams
- No moving parts
- Improved ground clutter rejection & spectrum width
- Possibility to replace disparate systems with a single multi-function system
- Solid-state technology and manufacturing advances may permit cost reductions



Why not Phased-Arrays?

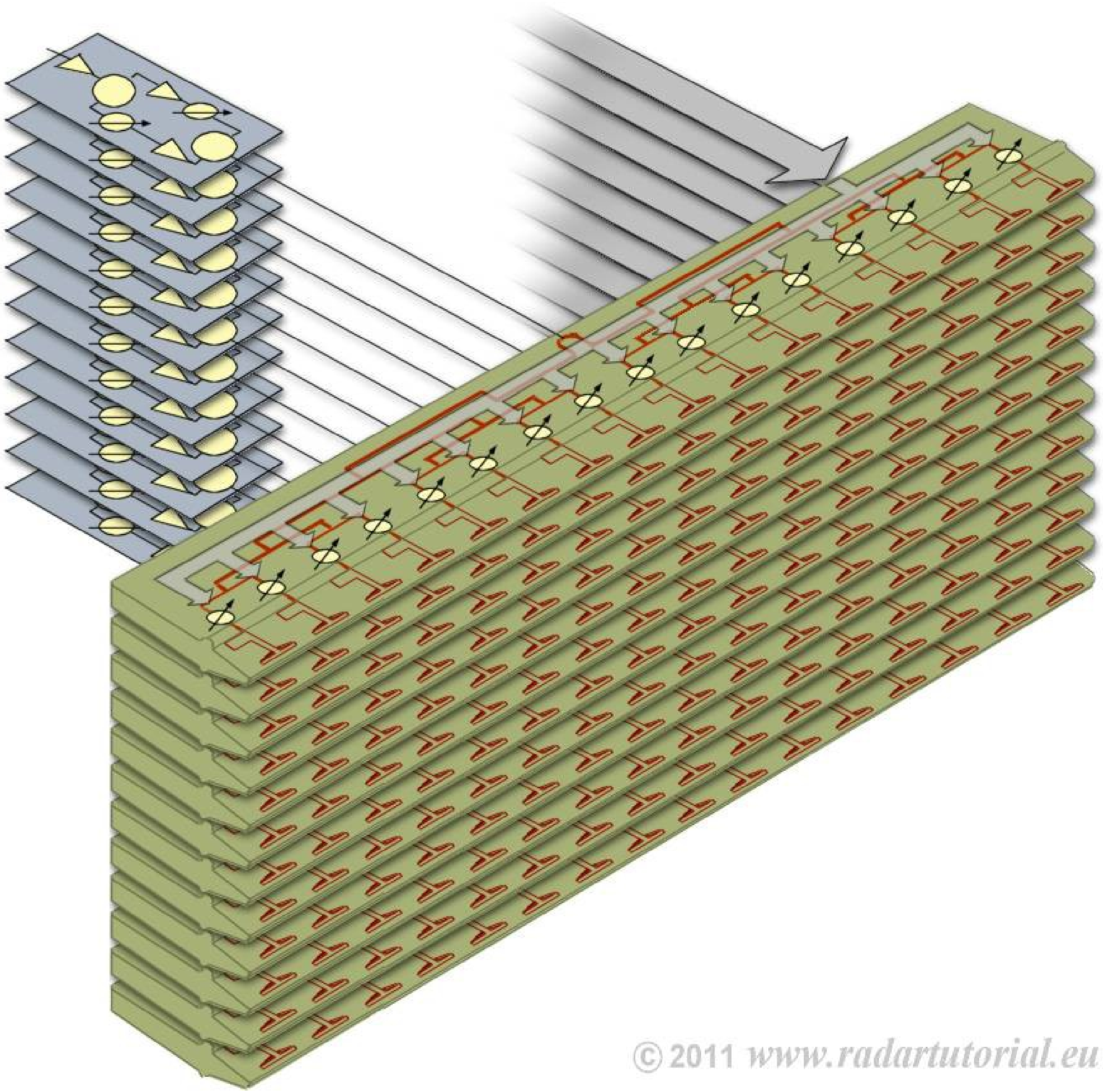
- Historically prohibitively expensive for civilian applications (~$1M/m^2)
- Weather is a “slow-moving” target
- PAR is less sensitive than a comparably sized dish
- Rapid scanning is possible with mechanical systems
- PAR has more complications
  - Gain, Beamwidth, Polarization all vary with scan angle
- Uncertainty in the market. Is it large enough to reap economies of scale (yet)?

Phased Array Fundamentals

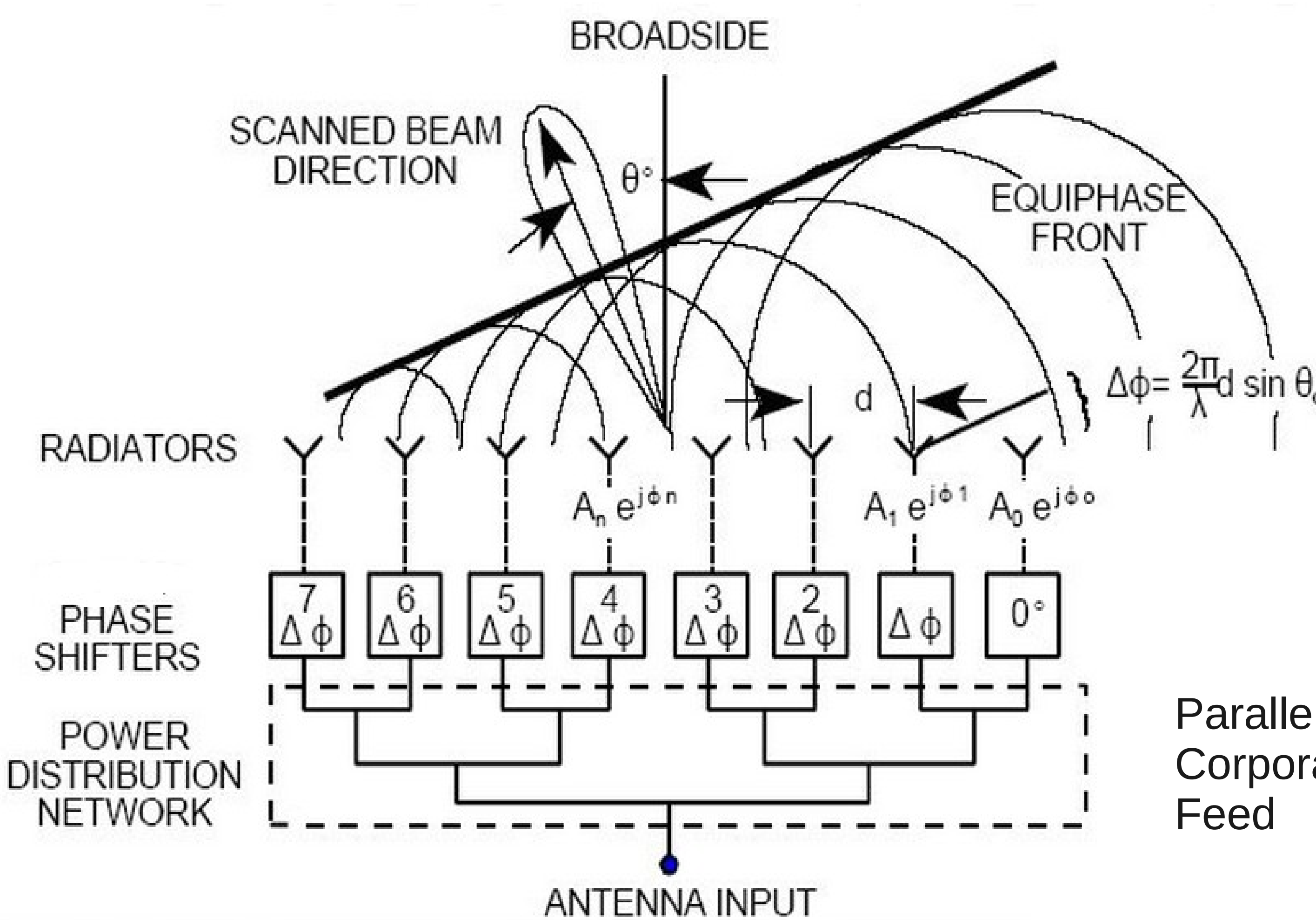


Arrays of Arrays

ROW / COLUMN
ARCHITECTURE



Passive Electronic Scanning Array (PESA)



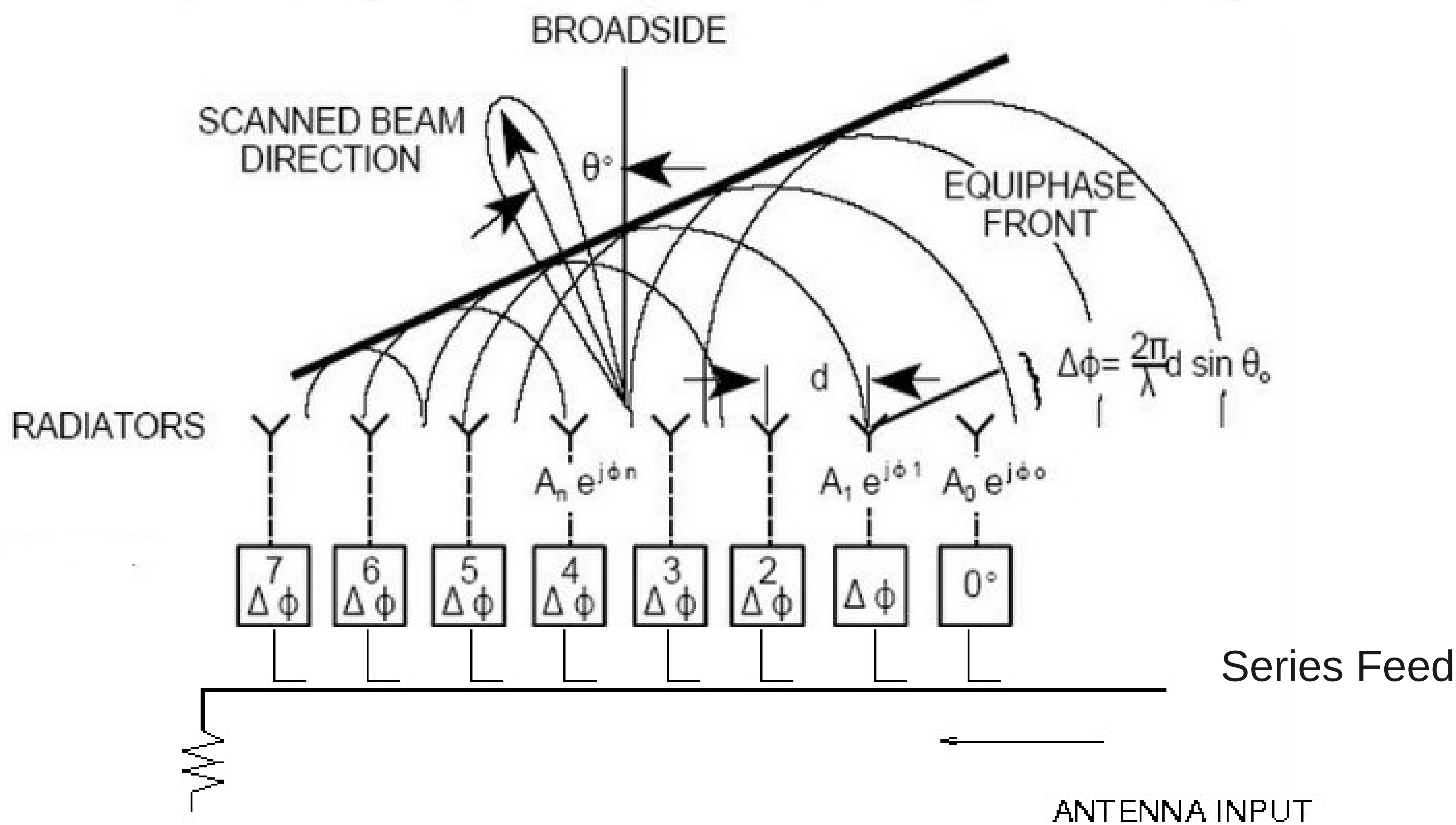
Parallel or Corporate Feed

TX/RX

EXAMPLE

- National Weather Radar Testbed (NWRT)
  - NOAA/NSSL, Norman, OK
  - SPY-1A (Aegis) radar panel w/WSR-88D transmitter & multi-channel receiver
  - S-band passive phased-array (4352 elements)
  - Single polarization
  - Ongoing experiments in rapid scanning, beam-multiplexing, spaced-antenna, sidelobe cancelling
    - Heinselman, P. L., and S. M. Torres, 2011, “High-temporal resolution capabilities of the National Weather Radar Testbed Phased-array Radar”. *J. Appl. Meteor. Climatol.*, **50**, 579-593.

Passive Electronic Scanning Array (PESA)



Varying the frequency can be used to scan.
Requires a large bandwidth.

EXAMPLE

- Rapid Doppler-on-Wheels
  - CSWR, Boulder, CO
  - X-band frequency-scan array of slotted waveguide antennas
  - 6-12 simultaneous beams
  - Single polarization
  - Frequency scan in elevation, mechanical in azimuth

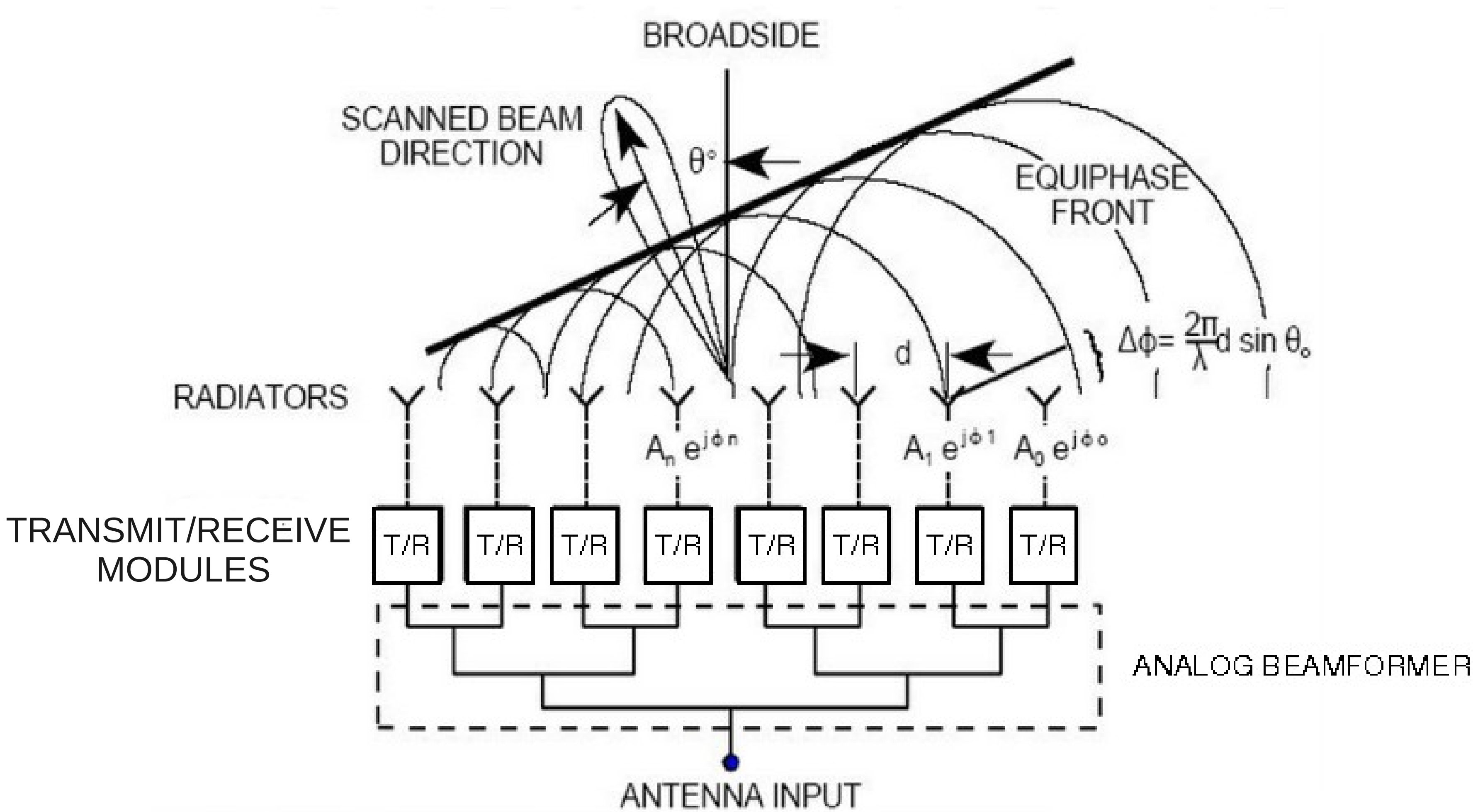
Hybrid Electronic/Mechanical Systems

- To reduce cost, a combination of electronic and mechanical scanning is common
  - Rapid DOW
  - MWR-05XP
  - OU-AIR
  - CASA Phase-Tilt
  - Toshiba
  - Thales

MWR-05XP
(Naval Postgraduate School/CIRPAS)

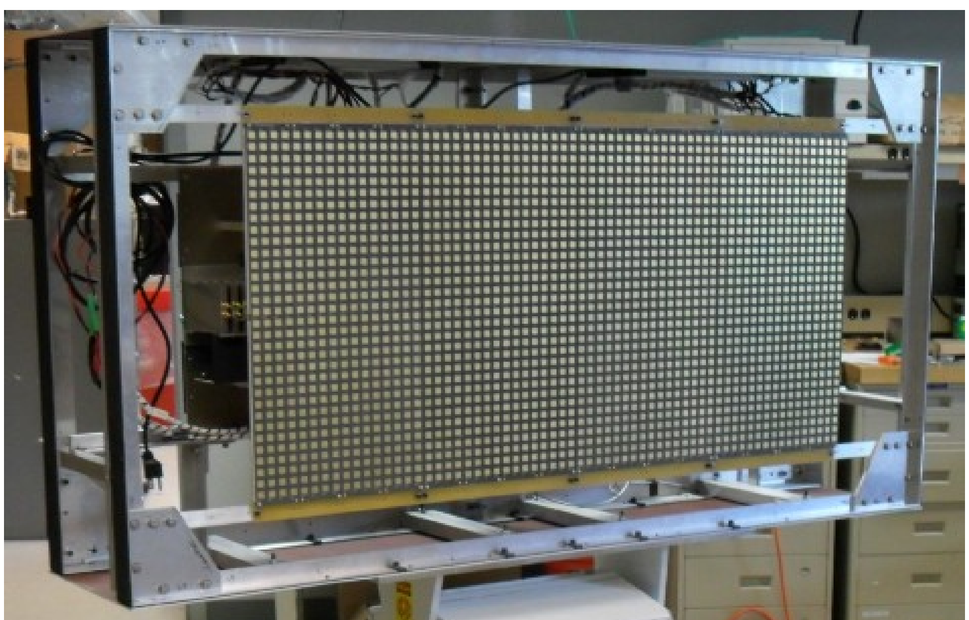
X-band
Re-purposed military radar
Phase scan (elevation)
mechanical scan (azimuth)

Active Electronic Scanning Array (AESA)



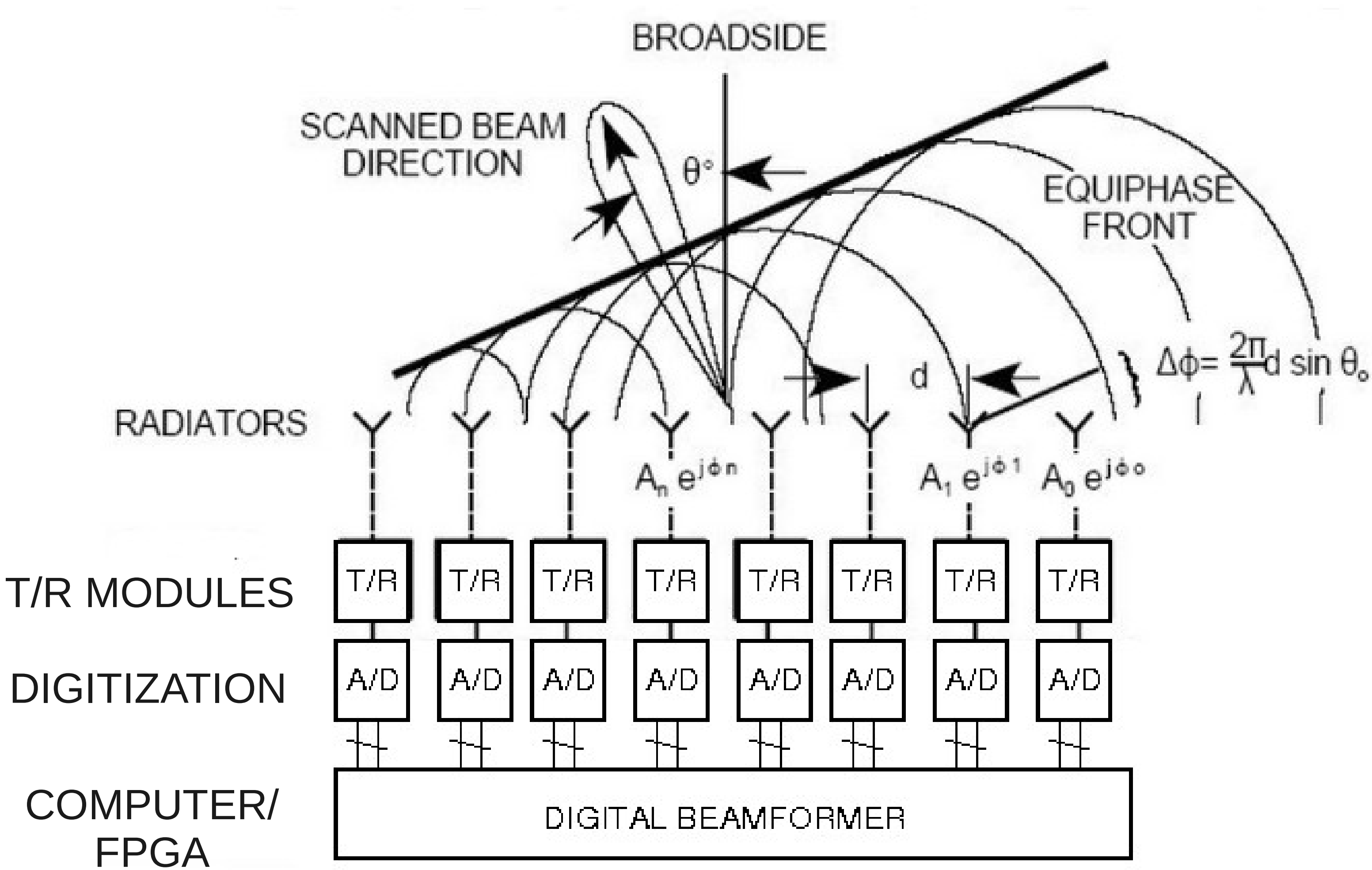
CASA Phase-tilt

- CASA ERC, UMass
  - X-band dual-polarization
  - Solid-state 64-element AESA
  - ATAR waveform



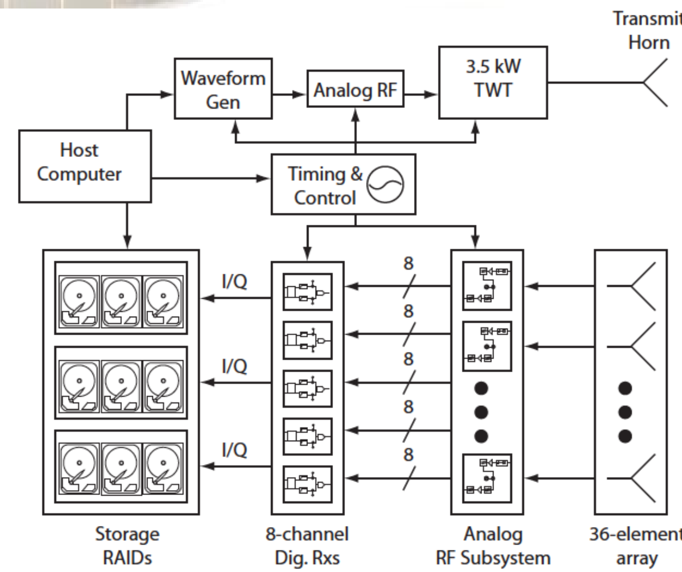
see CASA booth

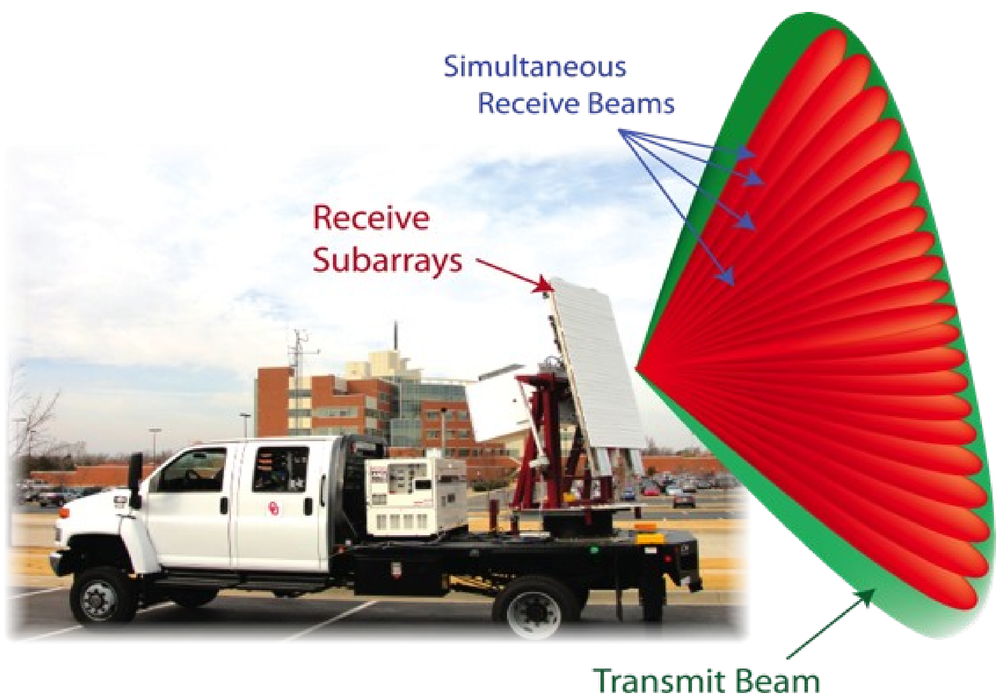
Digital Beamforming Array



OU - Atmospheric Imaging Radar

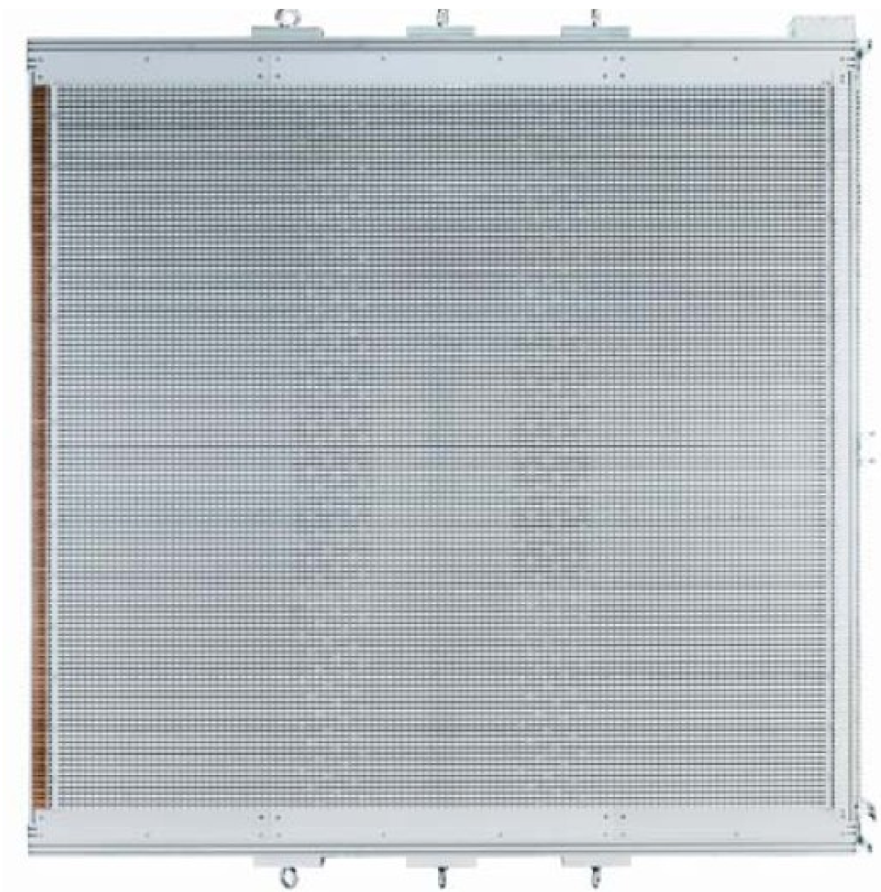
- Digital beamforming allows simultaneous measurements within the field of view (FOV) of the radar with an *infinite* number of beams
- X-band, 3.5 kW TWT, pulse compression, 1x25 degree FOV
- 36 independent I/Q receive channels, in-house design
- Clutter rejection via adaptive array processing

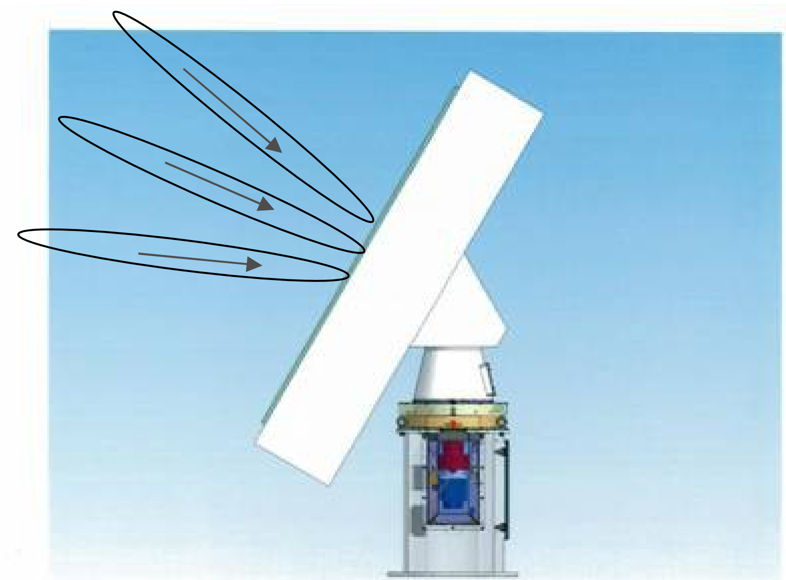




B. Isom, R. Palmer, R. Kelley, J. Meier, D. Bodine, M. Yeary, B. Cheong, Y. Zhang, Y. Yu, M. Biggerstaff, J. Atmos. Ocean. Tech., 2012

Development by Toshiba/NICT/Osaka U.





Mizutani, F., M. Wada, T. Ushio, E. Yoshikawa, S. Satoh, T. Iguchi, 2011, “Development of an active phased array weather radar”, *35th Conf. On Radar Meteorology,* 26-30 Sept., Pittsburg, PA, 14A.1.

Development by Thales

Fig. 8 (at left) Radar Sensors deployment at XP1 Trials campaign scheduled in Sept. 2012, (at right) new Multi-Function (wake-vortex, weather, traffic) Electronic scanning X-band Radar for XP1 trials at CDG airport

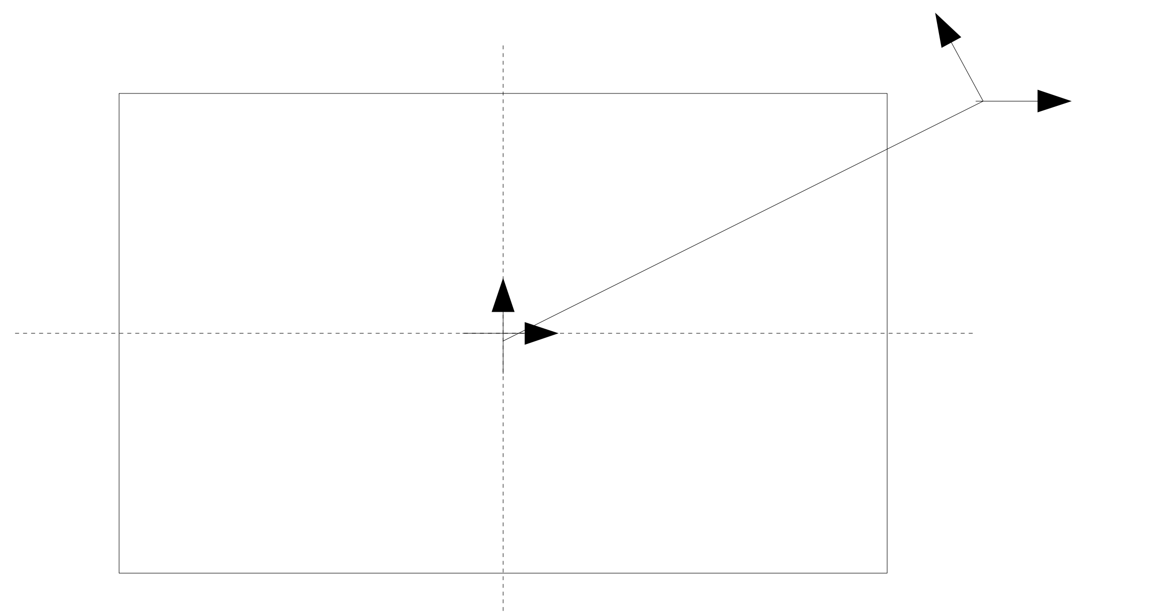
Barberesco et al. 4B.4

2D Electronic-Scanning, Dual-Polarized Systems

- MPAR – S-band dual-pol prototyping underway by MIT-Lincoln Laboratories
- Raytheon – X-band dual-pol. 2D AESA for ground-based/airborne applications

Calibration Issues

- Beamwidth: Θ_1, $\Phi_1 \sim 1/\cos(\Theta, \Phi)$
- Directivity (Gain): $G_D = 4\pi/(\Theta_1\Phi_1)$
- Polarization:
  - Biases in
    Z_{DR}, Φ_{DP}, ρ_{HV}, LDR

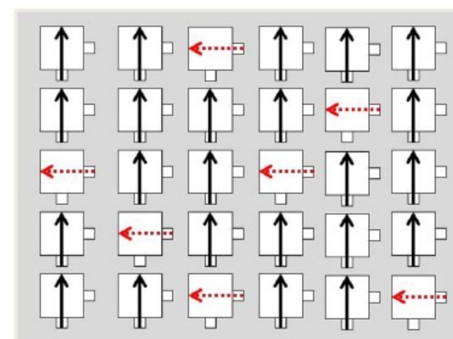


Approaches to Polarization Correction

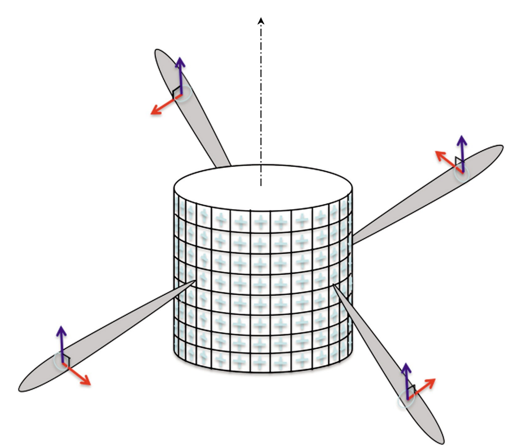
- Projection correction
  - Zhang et al., 2009, “Phased array radar polarimetry for weather sensing: A theoretical formulation for bias corrections”, *IEEE Trans. Geosci. & Remote Sensing,* **47**(11), 3679-3689.

$$\mathbf{S}' = \mathbf{C}^t\,\mathbf{S}^{(p)}\,\mathbf{C}$$

- Interleaved Sparse Arrays
  - Sanchez-Barbetty et al., 2012, “Interleaved sparse arrays for polarization control of electronically steered phased arrays for meteorological applications”, *IEEE Trans. Geosci & Remote Sensing*, **50**(4),1283-1290.

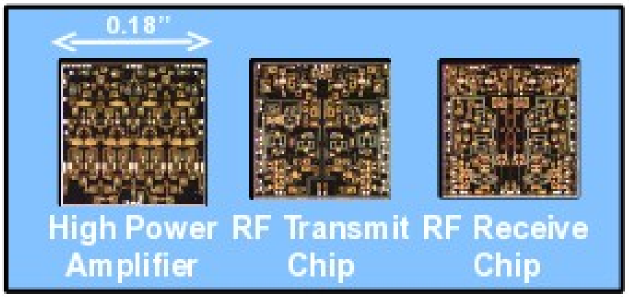


- Cylindrical Array Architecture
  - Zhang et al., 2011: “Polarimetric Phased-Array Radar for Weather Measurement: A Planar or Cylindrical Configuration?”. *J. Atmos. Oceanic Technol.*, **28**, 63–73.

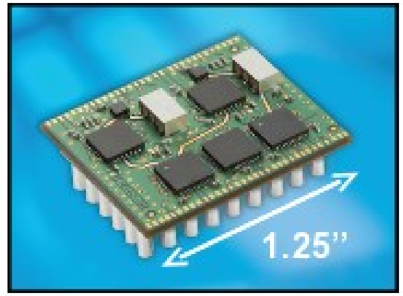


Multifunction Phased Array Radar Panel

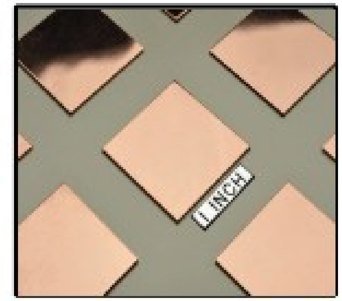
RF Chip Set



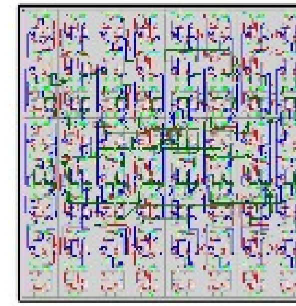
T/R Module



Radiator



Beamformer



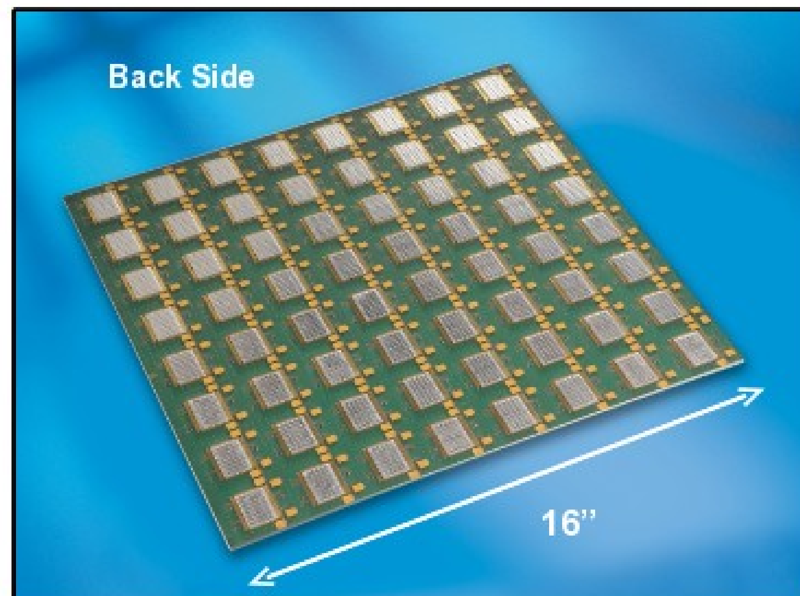
MPAR panel attributes:

- 2.7-2.9 GHz operating band
- 900 W peak RF transmit power
- Dual simultaneous receive polarization
- Low production cost (~$10K per panel)

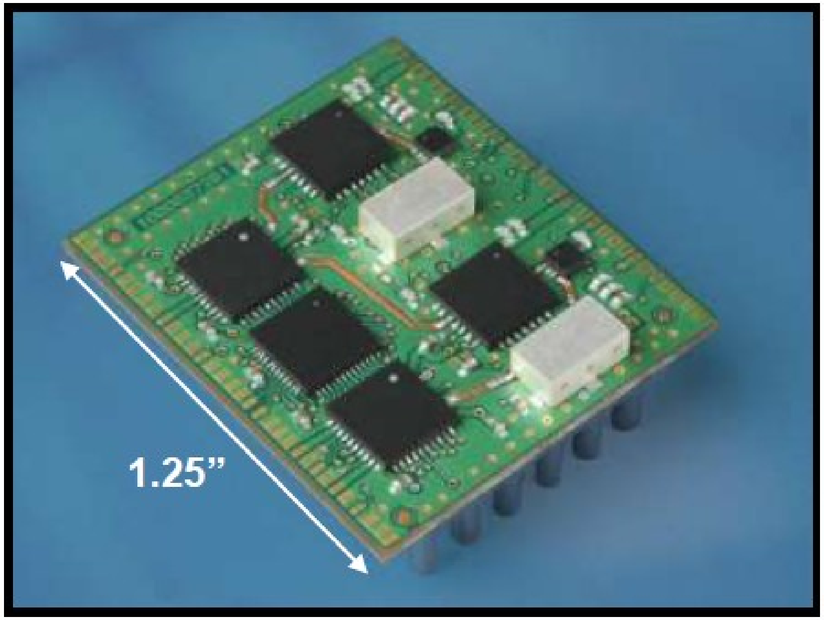
Low cost and high performance met by:

- Design for manufacturability
- Low cost T/R modules
- Scalable aperture design
- Digital subarray architecture

MPAR Panel

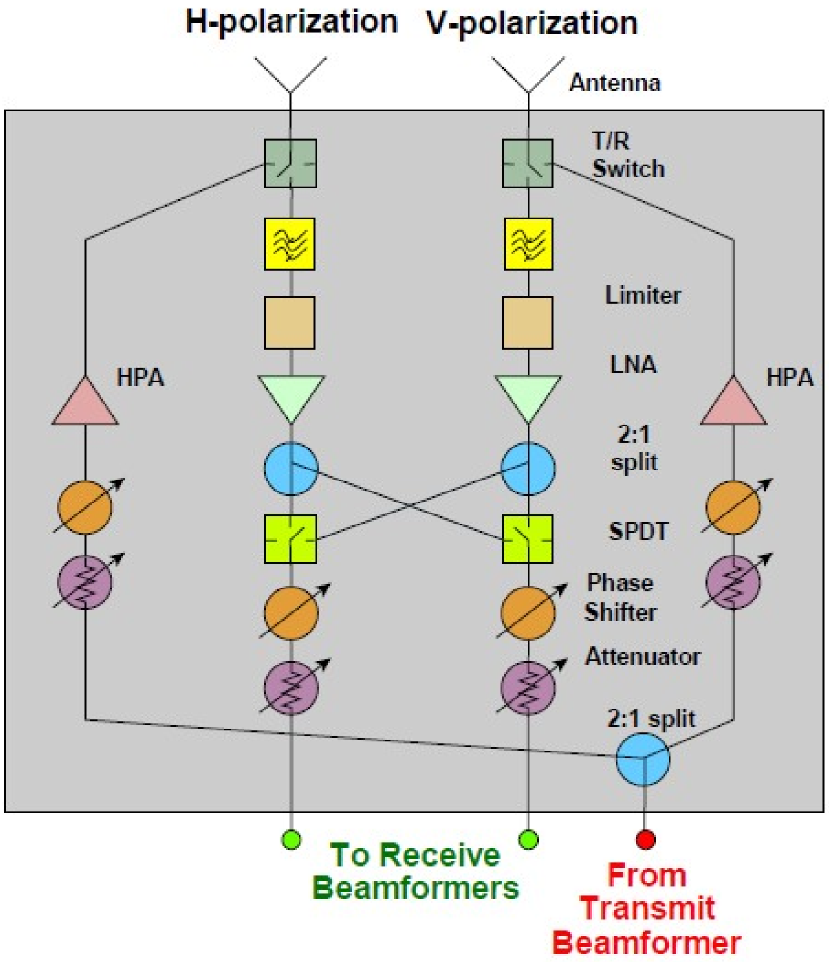


MPAR T/R Module



- **Polarization flexible**
  - Single dual pol or two linear pol beams
- **2.7 – 2.9 GHz operating band**
- **Plastic Quad Flat No-lead (QFN) RF packages for low cost**
- **Automated pick and place / assembly / test**
- **Low cost (< $25 ea)**
  - Based on current high volume wafer costs and automated assembly / test

MIT LL MPAR T/R Module

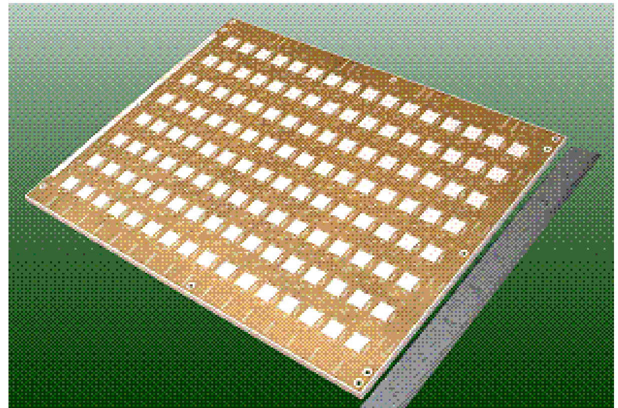


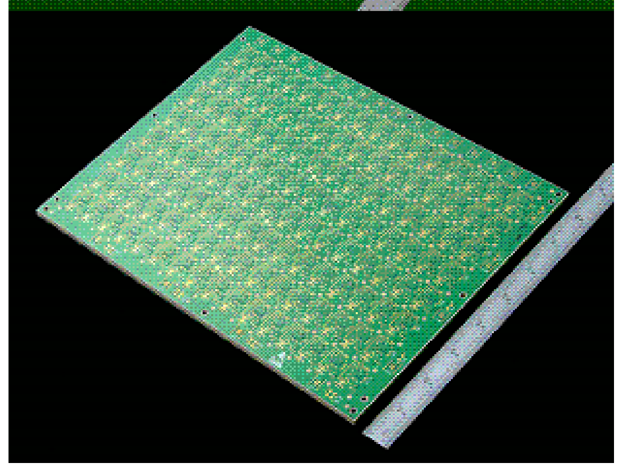
Raytheon

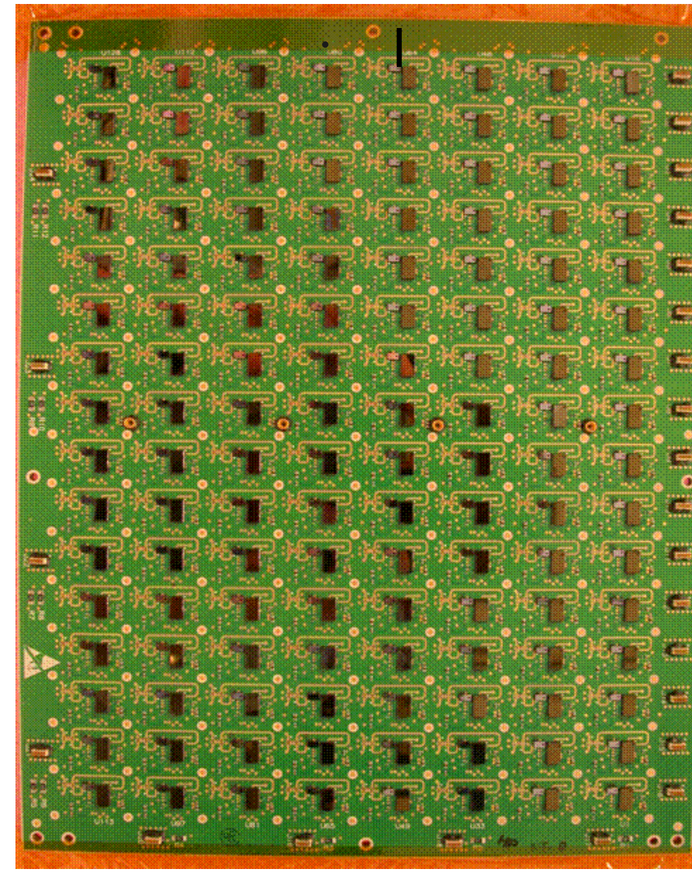
Demo Array – Panel CCA Assembly Overview

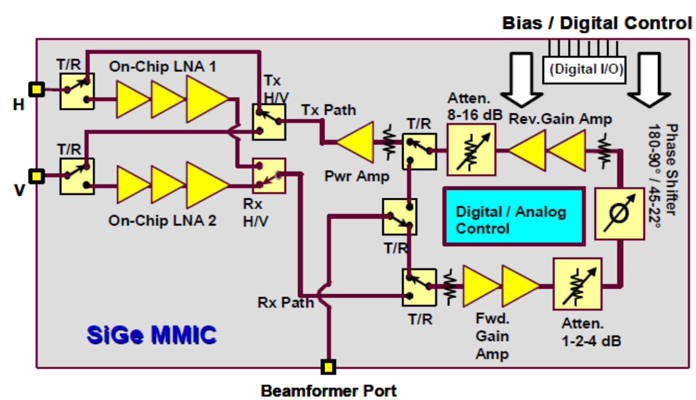
Weather Radar Transceiver MMIC design optimized for low peak power high duty cycle Target, Weather, and Wake Vortex Radar requirements

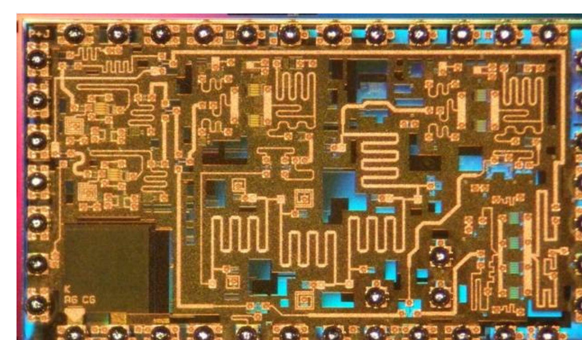
- Building Block Panel PWB consists of 128 identical unit cells
  - 18 layer board
  - Slot fed single Patch Radiator
- Each unit cell contains single SiGe Flip Chip, Linear Regulator, and associated Caps / resistors
- 4 Power, 4 Logic connectors and 1 RF Connector





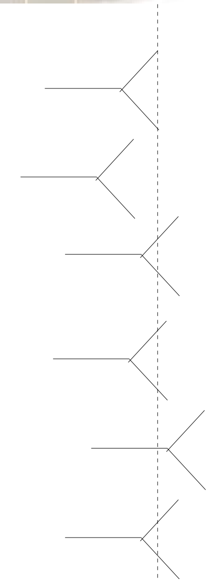


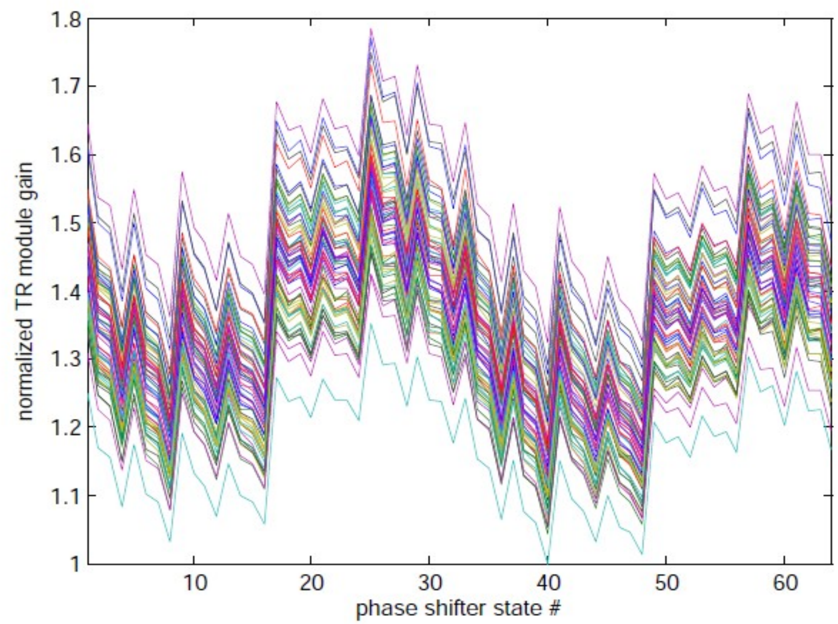




More Calibration Issues

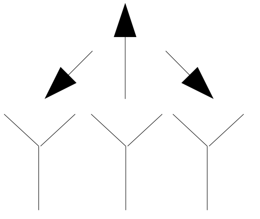
- Amplitude and phase errors at each element elevate sidelobes and cross-pol
- Errors may drift with temperature, age, …
- Need careful characterization
- In-place re-calibration





Approaches to Calibration

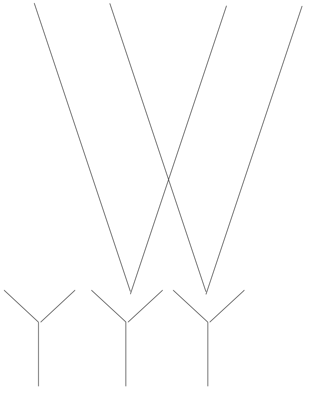
- Beacons or reference targets
  - e.g. Illuminators on periphery of array
- Exploit element-to-element coupling



  Aumann, H.M., A.J. Fenn, and F.G. Willwerth, 1989, "Phased Array Antenna Calibration and Pattern Prediction Using Mutual Coupling Measurements", *IEEE Trans Antennas & Propagat.*, **37**(7), 844-850.

  - Approach under investigation for CASA phased array.

- Spatial correlation properties of clutter



  Attia, E.H., and B.D. Steinberg, 1989, "Self Cohering Large Antenna Arrays Using the Spatial Correlation Properties of Radar Clutter", *IEEE Trans. Antennas & Propagat.*, **37**(1), 30-38.

  - Technique proven useful for digital beamforming systems

Outlook

- Phased-array weather radars have arrived.
- Low-cost rapid-scan systems incorporate mechanical scanning.
- Fully phased arrays in development at S-band and X-band (at least)
    - Technical challenges remain:
        - signal routing, heat dissipation, manufacturing cost
- Amplitude/Phase/Polarimetric calibration will continue to be a key research area.

Acknowledgement

The following kindly provided material for this presentation:

Paul Ackroyd, Raytheon
Jeffrey Herd, MIT-LL
Krzysztof Orzel, UMass
Bob Palmer, OU
Rob Palumbo, UMass
Josh Wurman, CSWR
Guifu Zhang, OU
Frederic Barbaresco, Thales

Thank You.

EWR Radar

Oct 2011

EMPAR™ series multifunction X-band phased array radar is unveiled at the Meteorological Technology World Expo in Brussels.