Phased-Arrays: Basics, Past Accomplishments, Amazing Breakthroughs and Future Trends
Dr. Eli Brookner, Raytheon Company, USA

Covered are advances in phased-arrays leading up to the latest breakthroughs and amazing

future potential developments:

- **Array basics: array phase scanning, thinning, embedded element gain, array factor, subarray time delay steering, array elements, array blindness, mutual coupling, array feeds, limited field of view arrays.**
- **TPY-2/THAAD, Zumwalt Dual Band Radar, IRIDIUM, CAPTOR, AMSAR, APAR, RBE2, M3R, APQ-63(V)2, APG-79, XBR, all GaAs Monolithic Microwave Integration Circuits (MMIC) active electrically steered arrays (AESAs)**
- **Digital beam forming (DBF) SAMPSON, SMART-L, Elta EL/M-2488 4-faced 2500 elements/face and Australia CEAFAR 6-faced active arrays, the latter two at S-band, shipborne and doing digital beam forming (DBF) at the element level, a MAJOR BREAKTHROUGH.**
- **3-, 4- and 6-Faced Shipborne Arrays Around the World: USA, Israel, Netherlands, Japan, China, Australia**
- **Russia now has MMIC airborne arrays**
- **8th Wonder of the World – Sea Based X-band (SBX) 45,000 element AESA radar**

SEA-BASED X-BAND (SBX) RADAR

8TH WONDER OF THE WORLD

- **RADOME: 103 FT HIGH**
- **ANTENNA DIAMETER: 72 FT**
- **45,056 T/R MODULES**
- **RADAR: X-BAND PHASED ARRAY**

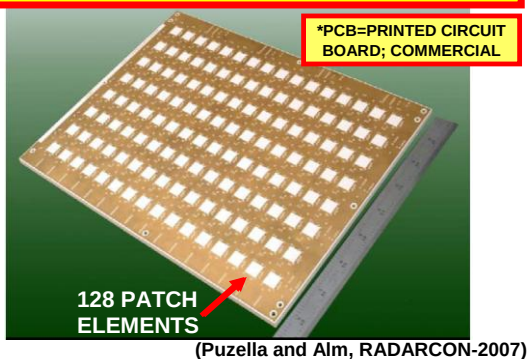
(SEE: COL J. R. FELLOWS, MILITARY RADAR CONF, JUNE 26-27, 2007)

Techniques for low cost arrays:

- **On a DARPA program low cost single chip T/R modules were developed at X and Ka-band costing respectively $10 and < $30, for peak powers of respectively >10mW and ~40mW**
- **Arrays using MEMS (micro-electromechanical systems) phase shifters**
- **Low cost 24 GHz phased-array car radars: only $100's!!!**
- **Microwave Integration at the extreme -- circuitry for 8 to 32 element array on single SiGe/BICMOS chip (Extreme MMIC)**
- **GaN technology (offers 10X higher power and higher efficiency; >1000 W peak with single transistor package,**
- **Low cost silicon based SiGe single chip T/R modules**
- **Raytheon low-cost X-band 128 element AESA panel building blocks using COTS**

(commercial off the shelf) PCB (printed circuit board) and flip-chip mounting

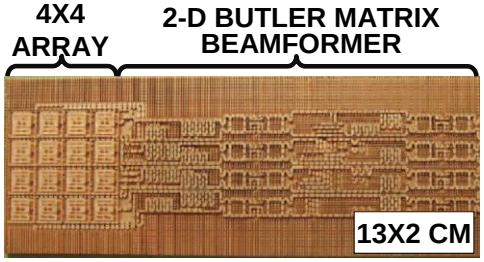
LOW COST X-BAND PCB* BUILDING BLOCK; 2.2 LBS, 7.4X10.1X0.21 INCHS



(Puzella and Alm, RADARCON-2007)

- **Purdue University low-cost S-band two panel GaN Digital Array Radar having 700 MHz bandwidth, 25 W per element peak; gets wide angle scan through use of EBG (electromagnetic band gap) material for increased isolation between antenna elements (lower mutual coupling); has potential of eliminating circulator**
- **Advantages of DBF**
- **Revolutionary 3-D micromachining could for some applications potentially reduce need for large scale MMIC integration while yielding advantages of eliminating bond wire parasitics, increase yield, ease repair; have put whole 4x4 35 GHz element array and its Butler matrix feed on single 13x2 cm^2 'chip'; pairs of micromachined coax lines provide 15 dB better isolation than conventional microstrip lines from 10 GHz to 60 GHz with a factor of 85 times smaller pitch**

3D MICROMACHINED KA-BAND "SINGLE CHIP" 16 ELEMENT ARRAY & BEAM FORMER



(Z. POPOVIC, ET AL, 2/08, MICROWAVE J.)

- **1. Common back end for 2-frequency shipboard radars and 2. COTS Supercomputer for signal processing; both a first.**
- **DARPA ISIS Million element 100x30 m^2 X-band AESA in aerostat at 70,000 ft; also operates at UHF; look down geometry allows it to see low flying target coming over the horizon. Lockheed awarded April, 2009, $400 m contract for 1/3 rd scaled aerostat**
- **STAP: Lowers antenna sidelobes by 6dB; knowledge aided STAP provides 10-15dB higher SNR using a priori info**
- **SweepSAR: JPL breakthrough for achieving very wide swath at lower cost using large reflector and array feed which allows multiple receive beams**
- **Real world radar applications for MIMO (Multiple Input, Multiple Output)**
- **Arrays with instantaneous bandwidths of 10:1 and 33:1**
- **Increasing receiver dynamic range by 20 db as limited by intermodulations produced by receiver and A/D nonlinearities; effectively 20 year advance in A/Ds because the**

advance is normally 1 bit every 6 years

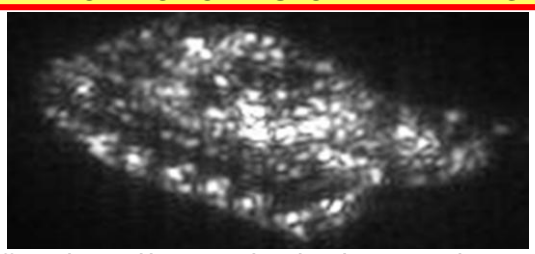
DARPA ISIS Million Element 100x30 m^2 X-band AESA in Blimp At 70 kft; Also Operates at UHF

1 SOLAR PANELS 2 PROPULSION 3 RADAR ARRAY 747

Also covered are:

- **4" resolution SAR (synthetic aperture radar) imaging at 3.5 km range**
- **1 cm resolution ISAR (inverse SAR) imaging with upgraded Haystack**
- **High resolution motion compensated ISAR image of tank moving over rough terrain using principal eigenvectors of matrix formed by tracks of major scatterers; also by using S-method; also by using road info and Kalman tracker**
- **UAVSAR, two pass interferometric SAR**
- **MEMRISTORS: Do what brain does in a shoe box**
- **Metamaterials: Can be used to make conformal arrays where otherwise not posssible; can make "Superlens Lens" which focuses beyond diffraction limit at optical wavelengths; potentially can stealth targets; used commercially in wireless router where it reduces size of antennas (8 of them) by large amount and increases isolation between the antennas**

HIGH RESOLUTION IMAGE OF TANK OVER ROUGH TERRAIN USING MOTION COMPENSATION BASED ON PROMINENT SCATTERER HISTORIES TO GENERATE EIGENVECTORS THAT PROVIDE TANKS RANDOM MOTION HISTORY -- AMAZING!!!



(Stuff, Sanchez, et al in Dr. W. Nel, et al, Radar 2009, Bordeaux, France)

- **Light modulators on Si enabling supercomputer on a chip**
- **Carbon transistors with 1000X clock speed of Si transistors (terahertz vs. GHz)**
- **Solid state transmitter replaces magnetron in ship borne navigation radar**
- **$80 baseball speed radar, $20 toy speed radar**

Dr. Eli Brookner received his BEE from The City College of the City of New York, ’53, MEE and DrSc from Columbia University ’55 and ’62.

He has been at the Raytheon Company since 1962, where he is a Principal Engineering Fellow. There he has worked on the ASDE-X radar, ASTOR Air Surveillance Radar, RADARSAT II, Affordable Ground Based Radar (AGBR), major Space Based Radar programs, NAVSPASUR S-Band upgrade, CJR, COBRA DANE, PAVE PAWS, MSR, COBRA JUDY, THAAD, Brazilian SIVAM, SPY-3, AEGIS, BMEWS, UEWR, Surveillance Radar Program (SRP), marine radars and COBRA DANE Upgrade. Prior to Raytheon he worked on radar at Columbia University Electronics Research Lab. [now RRI], Nicolet and Rome AF Lab.

He received the IEEE 2006 Dennis J. Picard Medal for Radar Technology & Application “For Pioneering Contributions to Phased Array Radar System Designs, to Radar Signal Processing Designs, and to Continuing Education Programs for Radar Engineers”; IEEE ’03 Warren White Award; Journal of the Franklin Institute Premium Award for best paper award for 1966; IEEE Wheeler Prize for Best Applications Paper for 1998. He is a Fellow of the IEEE, AIAA, and MSS.

He has published four books: Tracking and Kalman Filtering Made Easy, John Wiley and Sons, Inc., 1998; Practical Phased Array Antenna Systems (1991), Aspects of Modern Radar (1988), and Radar Technology (1977), Artech House. He gives courses on Radar, Phased Arrays and Tracking around the world (25 countries). Over 10,000 have attended these courses. He was banquet speaker and keynote speaker nine times. He has over 110 papers, talks and correspondences to his credit. In addition, he has over 80 invited talks and papers.