DARPA MMW System programs and how they drive technology needs

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What I hope to Discuss Today

• Review what the atmosphere actually is like – it is a primary concern for system designers

• DARPA/MTO programs above 100GHz which have inspired DARPA system programs.

• Example DARPA programs that are extending the state-of-the-art in MMW technology
The First Popular Chart of Atmospheric Attenuation in the RF region


BEWARE! - This chart has been circulated by Hughes Electron Dynamics Division, Varian, and Millitech since the 1970’s with the “lower curve” incorrectly labeled as “30,000 ft” which in some versions was then changed to 9146 meters. OML has been distributing a “correct” version, based on Liebe’s MPM93, in the Microwave Journal.

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Previously presented by the author at SPIE DSS 2006
What it really looks like

Atmospheric Attenuation

Attenuation (dB/km)

Frequency (GHz)

- RAIN
- 2XSTD
- STD
- FOG

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Previously presented by the author at SPIE DSS 2006
The Six “Bs” of MMW Attenuation

Typical weather conditions for different geographic locations
Terahertz Electronics

Solid – State THz Electronics

THz InP Transistors
- Smallest HEMTs: sub-30 nm gates
- Fastest HEMTs: $f_T \sim 0.7$ THz
  $f_{\text{max}} \sim 1.4$ THz
- Fastest HBTs: $f_T \sim 0.55$ THz
  $f_{\text{max}} \sim 1.2$ THz

THz Link Demonstrations
- Proof of concept digital wireless links have been demonstrated at 0.22 THz, 0.67 THz, and 0.85 THz

Vacuum THz Electronics

High Power Amplifier Performance
- HiFIVE result output power of 55.5 W at 0.214 THz
- Output power of: 132 mW at 0.64 THz
  50 mW at 0.84 THz
- Greater than 10 GHz instantaneous bandwidth at 0.67 THz and 0.85 THz
- Greater than 83% & 60% beam transmission at 0.67 THz and 0.85 THz
- Collector efficiency of 93% at 0.67 THz

THz Monolithic ICs. Packaged 10-Stage LNA shows peak gain of 14.7 dB at 830 GHz. Source: Northrop Grumman

Traveling Wave Tube (TWT) amplifiers with micromachined interaction circuits. Source: Northrop Grumman

Achieve device and integration technologies to realize electronic circuits operating at and beyond 1THz

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Scalable Millimeter-Wave Arrays for Reconfigurable Transceivers (SMART)

- Demonstrate an integrated, multi-layer, (3D) surface-emitting (panel) architecture for millimeter-wave (MMW) transceiver arrays to greatly reduce packaging complexity and to form arbitrarily large arrays

- Silicon interposer and wafer-level package integration approaches have been developed and demonstrated

- High yield, good reliability, and low cost manufacturing process is under development through assembling large numbers of SMART modules

Enabling compact, low-cost, reconfigurable, active electronically steerable arrays
Enable monolithic, high power efficiency, high linearity, silicon-based microwave/millimeter-wave transmitter integrated circuits (ICs) for next-generation military microsystems.
High Frequency Integrated Vacuum Electronics (HiFIVE)

Objective
Develop the first all-integrated (“chip-scale”) vacuum electronic devices for high-power millimeter-wave sources

Technologies
• Si micromachining
• High aspect-ratio interaction structures
• Integrated, high current density cathodes

Impact
• High bandwidth, LPI communication systems
• High-resolution radar
• Manufacturable vacuum electronics process based on standard MEMS rather than custom & expert machining

Today:
High frequency sources are large, expensive, and performance-limited

HIFIVE Phase II
• 220 GHz
• 50 W
• “MPM” level of integration (compact module)*
• 250 W-GHz Power bandwidth product

HIFIVE Phase III
• 220 GHz
• 50 W
• Fully integrated*
• 500 W-GHz Power Bandwidth product

* MPM = Microwave Power Module

* Cathode, gun, interaction structure, collector, driver, HV source

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Mobile Hotspots

Millimeter-wave Backhaul Links
- Frequency: 71 to 86 GHz
- Steerable millimeter-wave antennas
- Efficient power amplifiers (10 W)
- Air-to-air range > 50 km @ 1 Gb/s
- Air-to-ground range > 40 km @ 1 Gb/s

Aerial and Ground Hotspots
- Reliable, self-forming network
- Shadow UAV-compatible air node
  - Two under-wing pods
  - Weight < 25 lbs per pod
  - Power < 250 W per pod
- Humvee-compatible ground node
- Hotspot-to-handset: 4G LTE

Mobile Hotspots uses 1 Gb/s backhaul links to provide deployed forces with 4G-equivalent capacity

UAV: Unmanned Aerial Vehicle
LTE: Long-term evolution

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Millimeter-wave Amplifiers with Output Power > 20 Watts

Performers
- Raytheon RRI, Rancho Cucamonga, CA
- HRL, Malibu, CA
- Teledyne, Thousand Oaks, CA
- Millitech, Northampton, MA

Key Metrics
- Frequency of Operation (E-Band, 70 – 86 GHz)
- Output Power (>10 W)
- Power Added Efficiency (>20%)

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100 Gb/s RF Backbone (100G)

High-Order Modulation
• mmWave Frequency: 85 GHz
• Bandwidth: 5 GHz
• 25 Gb/s per channel
• ≥ 5 bits/s/Hz

Multiple Input Multiple Output (MIMO)
• Operates at or beyond the Rayleigh Range
• Multiple (4 to 8) independent channels

100G combines high-order modulation and MIMO to achieve 100 Gb/s to 100 km

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Motivation: Enable US Rotary Wing Aircraft forces to fight effectively in severely Degraded Visual Environments (DVE) when our adversaries cannot

Goal: Develop an electronically-agile radar to address all elements of combat including landings, takeoffs, navigation, lethality and survivability with the flexibility of adding new mission functions, all while reducing SWAP & cost

Approach:

- Develop phased arrays using silicon based tile technology to provide the complex architectures required for multi-functionality affordably
- Implement software re-definable operations to enable adaptable RF functions as required by mission or platform needs
- Create a synthetic vision backbone to register and fuse sensor data with high-resolution terrain databases and present the information to the pilots
System Design for Low SWAP Multifunction Array

Solutions to be Demonstrated:
- Array control to enable reconfigurable dynamic timeline
- Flip chip Subarray manufacturing to reduce touch labor and lower cost
- Array control layer constructs allow looping of repetitive commands to further reduce timeline necessary to control hardware
- Multi channel compact receiver converts RF to digital to take advantage of less expensive digital reconfigurable beamformer
- Front End Processor (FPGA) layer enables 3rd party mode support by requiring fewer software commands to control 28,000 Element Array

64 Element Tile
- -1 dBm power/element CP
- 13.7 dB Tile NF
- Dual Linear, LHC, RHC
- Tile and element level phase shifters and attenuators

24,576 Element Large Antenna Array

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IBM approach to a W-Band Silicon Tile Array

IBM Research: SiGe BiCMOS W-Band Phased-Array IC Architecture

- Receiving signals simultaneously in 2 polarizations from 16 dual-polarization antennas requires 32 Rx front-ends.
- Minimizing IC area will require sharing as much Tx and Rx RF front-end circuitry as possible.
- On-chip up/down conversion and a frequency multiplier for the LO are used to reduced the frequency of board-level signals.
Advanced Rotary Multifunction Sensor

Current Design Weight = 67 lbs
- Program goal is <175 lbs
- 40% of Weight for Power Supply and Cooling System

Current Design Power = 4.6kW
- Program goal is <8 kW

Current Design Cost = $550K
- Program goal is ~$100-200K
- 35% is Tiles – primarily testing

Current Design Volume ~1.4 ft³

Additional SWaP-C efforts to focus on:
- Reducing the cost of testing the tile (20% total savings)
- Reducing the power consumption of the tile (saves 30% weight, 50% power)

Greatest program risk is integrating Silicon Tiles into larger Arrays in a reliable fashion

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Tactical Implementation Will be Achieved with Improvements in Silicon Processes

- A Highly integrated tile must exhaust heat to cold plate that could be as warm as 50°C
  - Base of Si based devices must be < 75°C to maintain performance
  - 25° rise through entire system (heat exchanger, tiles) requires lower dissipation tiles
  - A more efficient process is required – higher gain per active stage
- For a Tactically insertable (air cooled) 12.9”x8.6” Antenna the heat density of the MMICs must be reduced from 29W/in² to 16W/in²
  - Current 2W 16 element MMIC must be reduced to 1W
- The only alternative which will permit air cooling is to reduce functionality.

IBM SiGe
  - 8HP
  - 8XP
  - 9HP

IBM CMOS
  - 45nm SOI
  - 32nm SOI
  - 11nm FinFet

Processes may meet requirements

Numerous other processes may exist which will reduce heat density

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ViSAR: Engaging maneuvering ground targets through clouds

Electro-optic sensors cannot provide accurate air-to-ground targeting through clouds due to loss of contrast – a physics problem.

- In Kosovo, air support could attack ground forces in only 24 of 78 days due to cloud cover.

Existing radar systems can penetrate clouds but frame rates are too low (<0.1 Hz) to provide targeting against maneuvering targets – a technology problem.

<table>
<thead>
<tr>
<th>Region</th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korea East Coast</td>
<td>23</td>
<td>56</td>
</tr>
<tr>
<td>South Korea</td>
<td>24</td>
<td>40</td>
</tr>
<tr>
<td>Dinaric Alps</td>
<td>41</td>
<td>23</td>
</tr>
<tr>
<td>European Highlands</td>
<td>57</td>
<td>26</td>
</tr>
<tr>
<td>European Lowlands</td>
<td>52</td>
<td>24</td>
</tr>
<tr>
<td>Mideast Desert</td>
<td>19</td>
<td>2</td>
</tr>
</tbody>
</table>

Percentage of times cloud ceiling < 1km occurs for selected locations.

Program Goal: Develop and demonstrate an RF targeting sensor that will operate through clouds as well as current IR sensors do in clear weather.

Challenge: Achieve a 30 dB increase in transmitter power and/or receiver sensitivity

Current RF (0.05W) Electronics @220 GHz under cloudy conditions

Program Goal 50W over 231.5-235 GHz

Assumptions:
1. 0.2 m resolution.
2. 100 m Field of Regard (FOR).
3. Single person Target.

Increase in contrast achieved through improved Technology.

Operating around 230 GHz has other benefits:
Antenna size is inversely proportional to frequency
SAR images may be smoother and less specular, and thus more similar to EO/IR
SAR image formation processing requirements are reduced

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3 Elements of the DARPA program

Flyable electronics:
1. Medium power amplifier with bandwidth greater than the radiolocation band
2. Integrated receiver and exciters operating over 231.5-235 GHz replacing large waveguide structures
3. High power objective system amplifier which combines the medium power amplifier with a vacuum electronic power booster

Phenomenology experiments and a system simulation:
1. Measurement of clutter backscatter and Doppler spreading to support scene modeling
2. Analysis of Doppler from humans at appropriate frame rates to aid in ID of targets
3. Scene simulator to include moving targets, aircraft dynamics, and weather for testing processing functions
4. Investigation of new algorithms taking advantage of high frame rates

Develop a prototype SAR to replace IR Targeting Systems

1. Potential solution: integration of one transmit antenna and four receive antennas which should fit within a typical EO/IR Gimbal for flight testing of the concept
2. Potential for an RF tag so the Forward Observer can be identified in the Field of Regard
3. Demonstrate this capability on an AC-130J or surrogate

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Advanced Scanning Technology for Imaging Radars (ASTIR)

An opportunity exists to create a new imaging radar architecture which will:
• Provide high resolution 3D imaging for enhanced identification and targeting; independent of platform or target motion
• Produce video frame rates (>10 Hz) to compensate for image/target motion
• Reduce system complexity resulting in lower cost, power, and weight

ASTIR will result in more readily available, cost effective imaging radar capabilities for:
• Terminal homing seekers
• Target classification for force protection
• Personal imaging for detection of concealed weapons
• Other applications?

ASTIR will exploit recent developments to create a new imaging radar architecture
Proposed new architecture for imaging radar

A radar with a compound antenna structure:
- A primary aperture large enough to achieve required resolution
- An electronically scanned sub-reflector to provide high resolution within the Field of View (FOV)

Approach 1: Sub-reflector replaces an electro-mechanically scanned mirror

Approach 2: Sub-reflector electronically steers a small spot across the main reflector
- RF sampled at each spot location is processed using synthetic aperture techniques to reconstruct an image at any range in the FOV - digital image formation

Approach 3: Elements of the sub-reflector would be digitally modulated with orthogonal phase codes
- Electric field on each element would be decoded after reception and processed to permit digital beamforming
Elements of the program

BAA 14-53: Sub-reflector Technology Development
Industry and Academia

**TA1:** Develop sub-reflector technology for rapid control of radar beam characteristics
- Phase 1 - Design an electronic sub-reflector for a compound antenna with a single transmit/receive chain
- Phase 2 – Build and demonstrate a prototype electronic reflective scanner

**TA2:** Investigate sensor designs and processing approaches

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**Mission Analysis**
APL, IDA, Lincoln Lab, Navy, PNNL
- Determine specific applicable military needs
- Develop requirements for BAA 2

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**BAA 2 (FY16): Develop and demonstrate sensor for military missions**

1-2 demonstrations of sensors for specific military applications

Potential applications
- Defense of in the Littoral environments (small boat attack)
- Defense of land facilities against local incursion
- Monitoring personnel passage through access points in facilities
- Terminal Homing

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MMW needs to advance systems

- Low Noise, Power, PAE – always popular
- Linear, High Dynamic Range Mixers
- Balanced amplifiers for better matching
- Non-reciprocal devices
- Filters
- Interconnect technology
- Low-loss switches and phase shifters
- Low noise Oscillators
- Automatic testing of phased array tiles