Paper #49 Session 16. 2

Traveling-Wave Antenna Array (TWAA) with Multioctave Scan-Gain-Bandwidth*

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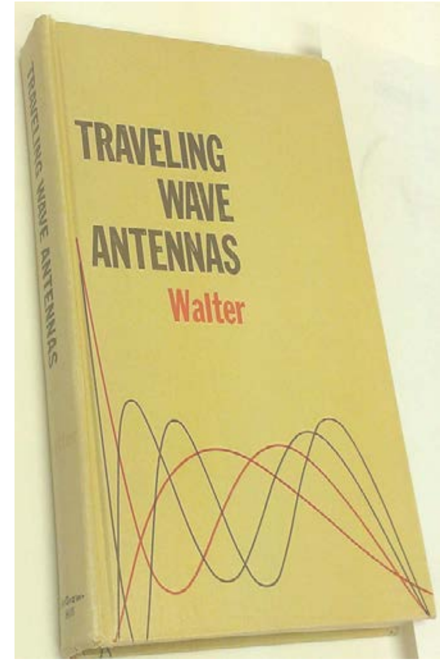
This presentation is dedicated to the late Prof. Buck (C. H.) Walter of The Ohio State University (OSU), author of "Traveling Wave Antennas," McGraw-Hill, 1965.

22 July 1924-10 March 2016; M.S. in Physics, 1951, Ph.D. in E.E. 1957, OSU; Director of OSU ElectroScience Laboratory 1977-1983; Fellow of IEEE; President of AP Society 1974.



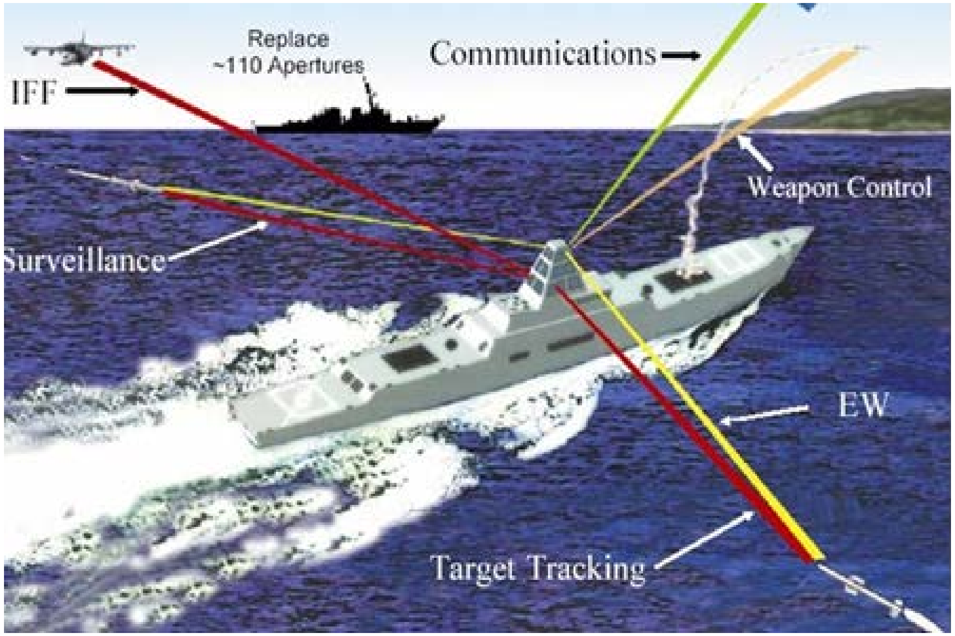
2013 IEEE Interna'l Symposium on Antennas & Prop.

Why
"Multioctave Planar Phased Arrays (MPPA)"?

- ***Planar**: The only practical way to implement phased arrays*
- ***Multioctave**:* Multioctave Scan-Gain-Bandwidth needed for
  - Broadband (fast and big data rate)
  - High security
    - cyber and physical spaces
    - defensive and offensive

MPPA's military and aerospace applications

- Planar structure for low-cost production, transport, and integration
- Multioctave bandwidth and ±60-deg scan desired for radar, EW, C4I, etc.

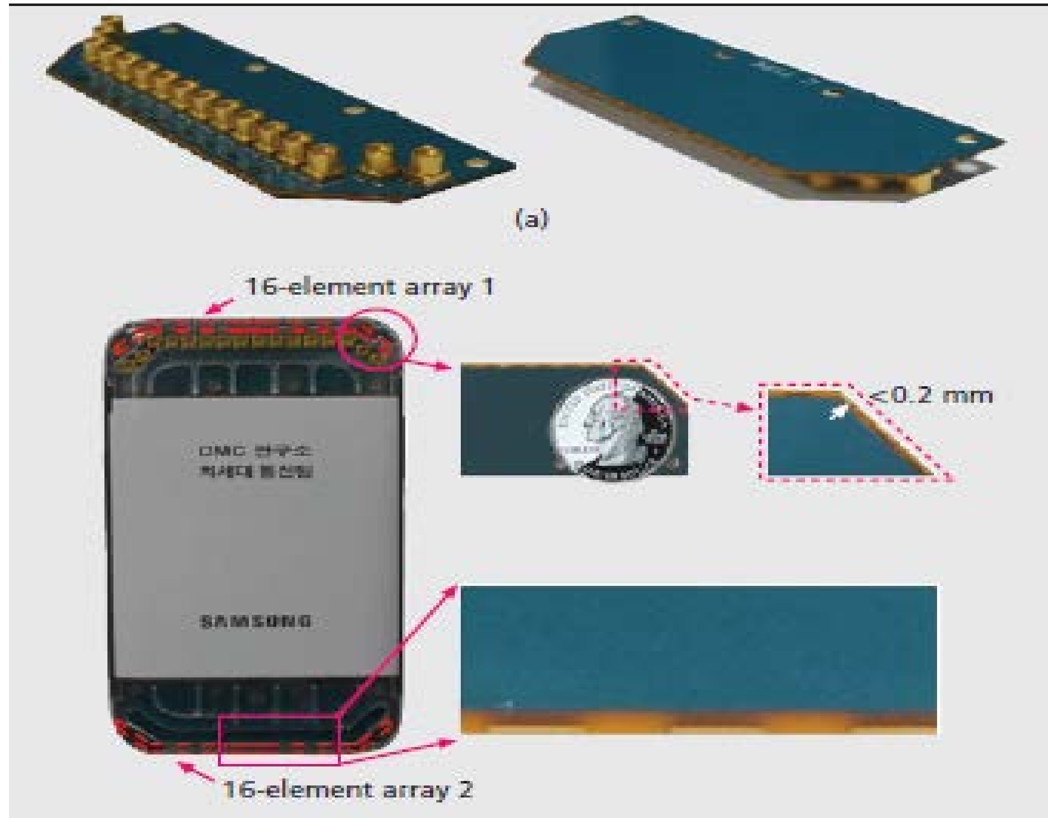


MPPA's new application in *5G* mmWave Wireless

- *5G* plans using phased arrays on cellphones at mmWave frequencies for
  - Big-data
  - IoT (Internet of Things)
  - Cloud
- **However, 5G could be devastated by security failures in cyber space!**

mmWave MPPA offers a physical layer solution!!!

A special session is being organized for 2017 IEEE AP-S URSI Symp.



W. Hong et al, "Study and Prototyping of Practically Large-Scale mm Wave Antenna Systems for 5G Cellular Devices," *IEEE Communications Magazine*, September 2014.

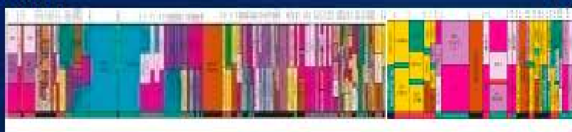
Samsung 16-element array demo at 28 GHz

Wider Bandwidth for 5G

Availability of More than 500 MHz Contiguous Spectrum Above 6 GHz

Below 6 GHz

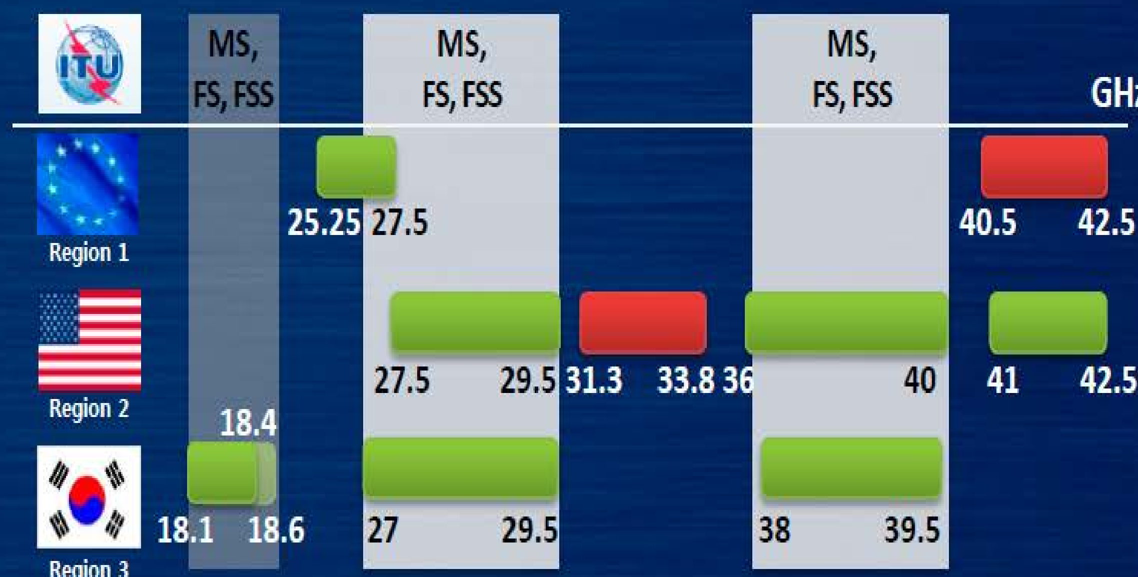
300 MHz 6 GHz



< 1 GHz [MHz]	410-430, 470-694/698, ***694/698-790***[1]
1-2 GHz [MHz]	1300-1400, ***1427-1525/1527***, 1695-1700/1710
2-3 GHz [MHz]	2025-2100, 2200-2290, 2700-3100
3-5 GHz [MHz]	3300-3400, ***3400-4200***, 4400-5000
5-6 GHz [MHz]	5150-5925, 5850-6245

Global Interest Bands for WRC-15

Above 6 GHz (Regional Recommendations from ITU)



Current Usage	Current Usage
US : LMDS, FSS EU : Fixed P-P Link, FSS Earth Station Korea : Maritime Use	US : Fixed P-P System EU : Fixed P-P Link Korea : Broadcasting Relay

MOBILE Primary

No MOBILE

[1] WRC-15 AI 1.2

MS : Mobile Service
FS : Fixed Service
FSS : Fixed Satellite Service
P-P : Point to Point
LMDS : Local Multipoint Distribution Service

MPPA concept is 70 years old

- Embryonic:1945-1964
  - H. G. Booker (1945)
    - No ground plane; largely a scattering concept.
- Larval:1965-2002
  - Current Sheet Antenna (CSA): H. A. Wheeler (1965)
  - Traveling Wave Antenna (TWA): C. H. Walter (1965)
- Adult (Technology Readiness Level (TRL) ≥ 4): since 2003 with grand hype!
  - **CSA***
    - Tightly Coupled Array (TCA): Munk (OSU); Tayler, Durham, Crosswell, Rawnick, Jones (Harris Corp)
    - Connected Array (CA): J. J. Lee, A. Neto et al., C. Baum, R. Hansen (The Raytheon Family according to Neto*)
  - **TWA** ⟹ Traveling Wave Antenna Array (**TWAA**): J. J. H. Wang (WEO)

*Based on Neto & Cavallo (2015)

Major R&D in MPPA before 2000

- CSA: reached 33% bandwidth
  - L. Grun and J. Pleva, "Multioctave Microwave Array," AFWAL-TR-84-1054, Raytheon Company, Bedford, MA, May 1984.
    - 10-14 GHz (33% bandwidth)
  - C. H. Hemmi et el, "Multifunction wide-band array design," *IEEE Trans. Antennas Prop.*, March 1999. (Raytheon today)
    - Focused on T/R module and BSN.
    - Array antenna demonstration only using Scan Element Gain (SEG) technique over C, X, and Ku bands — thus at TRL< 4.
- TWA: 10:1 bandwidth in constant element phase shifter; 22% array bandwidth
  - J. J. H. Wang et al, "A multioctave-band photonically–controlled, low-Profile, structurally-embedded phased array with integrated frequency-independent phase-shifter," *1996 IEEE Intern'l Symp. on Phased Array*, Boston, October 1996. (WEO)

Surprisingly, CSA bandwidth still < 1 Octave in 2015 !

(Due to high X-pol > -10 dB)

Neto, *2015 IEEE AP-S Symp.*, Vancouver

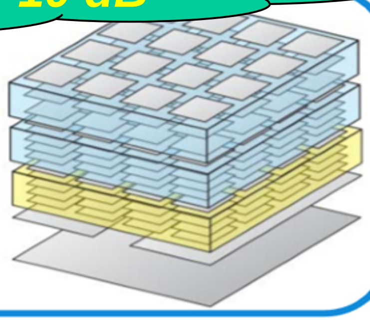
Conclusions

- Wheeler introduced the idea about 50 years ago
- we worked on it 13 years to understand them and solve feeding mechanisms
    - The understanding we now have about connected arrays is enormous with respect to what we ever had on Vivaldi's
    - Realistic Connected arrays give same BW and much lower cross polarization than Vivaldi's

To reduce X-pol to < -10 dB

- Next step is clearly using them with ADL super-layers

BW with efficient scans to 60 degrees from 30% to 60% (1 octave)



TWAA has reached 6:1 bandwidth*

Based on

- Measured data at WEO and Georgia Tech (GT)
- Computer simulation data by The Ohio State University (OSU)

*J. J. H. Wang, "Advanced Development of Traveling-Wave Antenna Array (TWAA) as Multioctave Planar Phased Arrays," *2016 IEEE Intern'l Symp. Antennas and Prop.,* Farjardo, Puerto Rico, June 26-July 1, 2016.

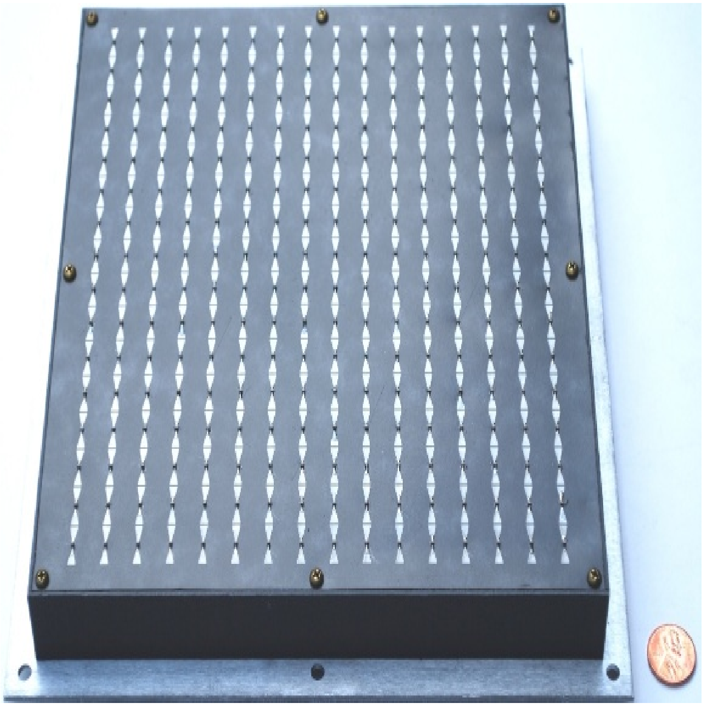
Pivotal advantages of TWAA over other MPPAs (CSA)

Features	TWAA	Other MPPAs (CSA)
Bandwidth and scan angle	Bandwidth: 6:1 (2-12 GHz scalable to other frequencies) wide scan to ±60°	Bandwidth < 2:1 (< 60% or 1 octave) for scan to 60° (due to high X-pol over -10 dB)
Use of dissipative or exotic material (e.g., ferrite or metamaterial)	Not used	Often needed/used; thus lower producibility, larger cost, weight & thickness
Use of substrates/ superstrates of special dielectric property	Not used (used only for structural support); thus lower cost, weight, thickness. Easily air cooled for high power!	Generally necessary; thus higher cost, weight, and thickness. Difficult to air cool, thus low power handling

Four prototype Traveling-Wave Antenna Array (TWAA) have been successfully developed and tested

- 16×16-element (U.S. patent #8,264,410 B1, 2012)
  - scalable to other numbers of elements and frequencies
  - 256 SMA connectors on back — ready for connection with a three-stage TTD BSN and T/R module.

Front view
WEO Model A135-001

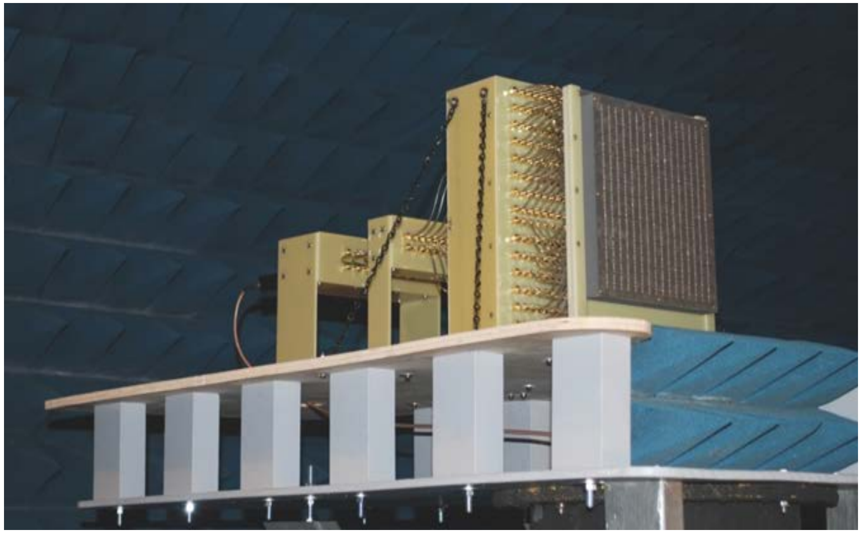


Back view showing
256 SMA feed connectors

Classical far-field tests with TTD BSN

- Far-field tests at anechoic chambers of WEO and Georgia Tech GTRI
- Using 2-18 GHz BSN (Beam Steering Network) developed at WEO
  - True-Time-Delay (TTD) lines using phase-matched semirigid coaxial-cable corporate feed network
- Discrete TTD lines
- Scan to

  0°, ±30°, ±45°, ±60°
- Test over 2-12 GHz
- 0.5 GHz increments



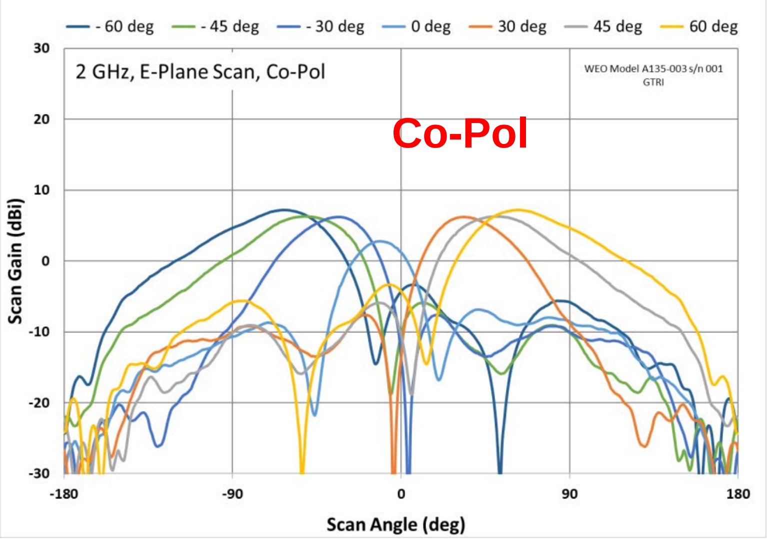
Key references of TWAA

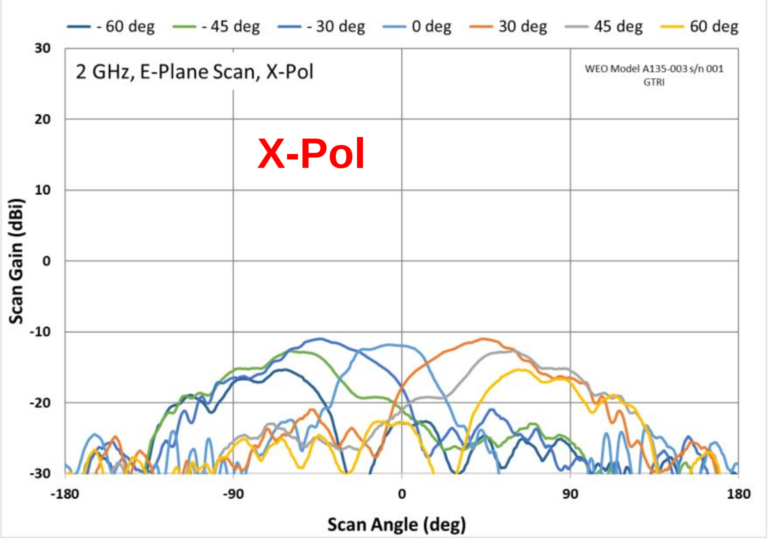
- J. J. H. Wang, "Planar broadband traveling-wave beam-scan array antennas," U.S. patent #8,264,410 B1, filed 31 July 2007, awarded 11 September 2012.
- J. J. H. Wang, "Broadband planar Traveling-Wave Arrays (TWA) with 2-D elements," 2010 IEEE Intern'l Symp. Phased Array Systems & Technology, Boston, MA, October 12-15, 2010.
- J. J. H. Wang, "Traveling-Wave Antenna (TWA) array as a thin Multioctave Planar Phased Array (MPPA)," 2013 IEEE Intern'l Symp. on Phased Array, Boston, MA, October 15-18, 2013.
- J. J. H. Wang, "Empirical and theoretical characterization of Multioctave Planar Phased Arrays," 2015 IEEE Intern' l Symp. Antennas and Prop., Vancouver, July 2015.
- J. J. H. Wang, "Demonstration of low-cost ultra-wideband planar phased array having multioctave bandwidth, wide scan, and high efficiency," FERMAT, V. 14, March-April, 2016. Available: http://www.e-FERMAT.org.
- J. J. H. Wang, "Traveling-Wave Antenna Array (TWAA)—a Multioctave Planar Phased Array (MPPA)," FERMAT, V. 16, July-August, 2016. Available: http://www.e-FERMAT.org.
- J. J. H. Wang, "Advanced Development of Traveling-Wave Antenna Array (TWAA) as Multioctave Planar Phased Arrays," 2016 IEEE Intern'l Symp. Antennas and Prop., Farjardo, Puerto Rico, June 26-July 1, 2016.

Measurement and Computation

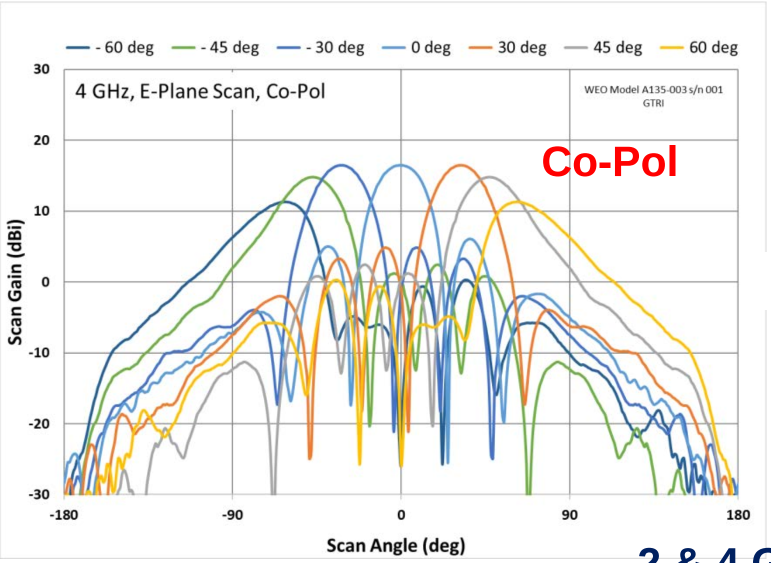
- Four prototypes of nearly identical design fabricated and tested
- Small discrepancies in measured performance between prototypes largely due to feed networks
- Computer simulation at OSU moderately handicapped by software, computer, and simplified feed model.
- Computational accuracy deteriorates with widening scan angles, thus not available for ±60°.

Measured array E-plane scan gain pattern 2-12 GHz

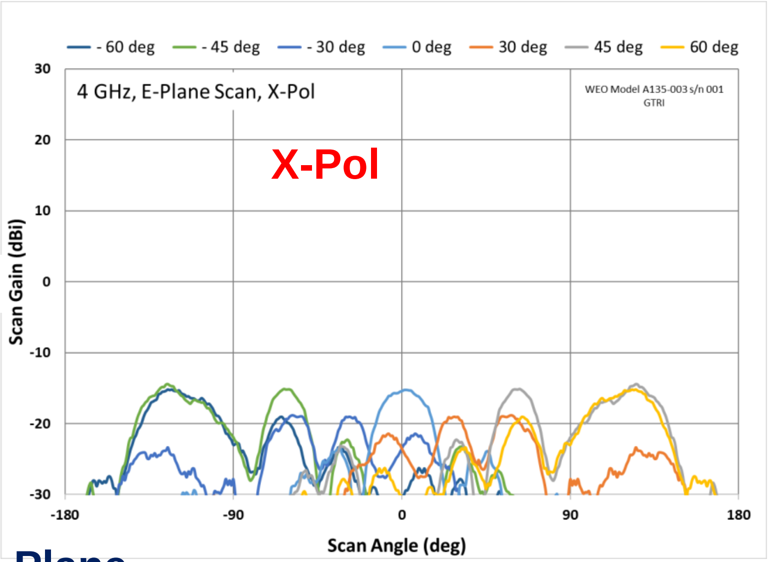




2 GHz

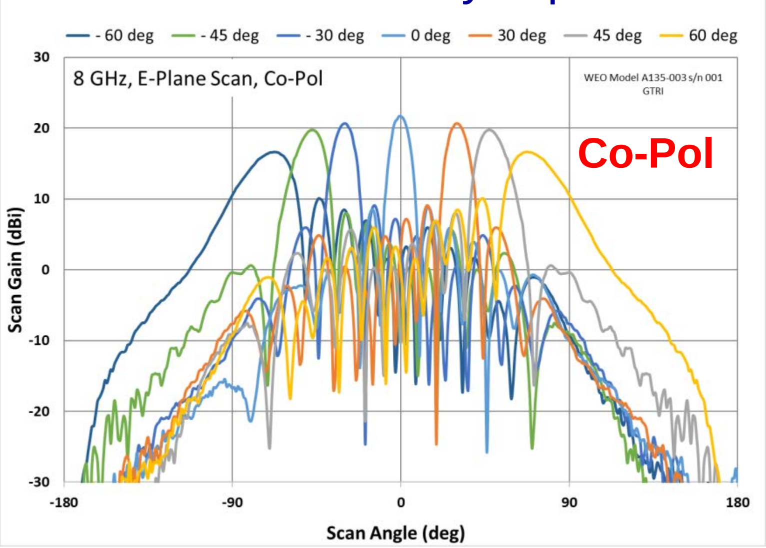


4 GHz

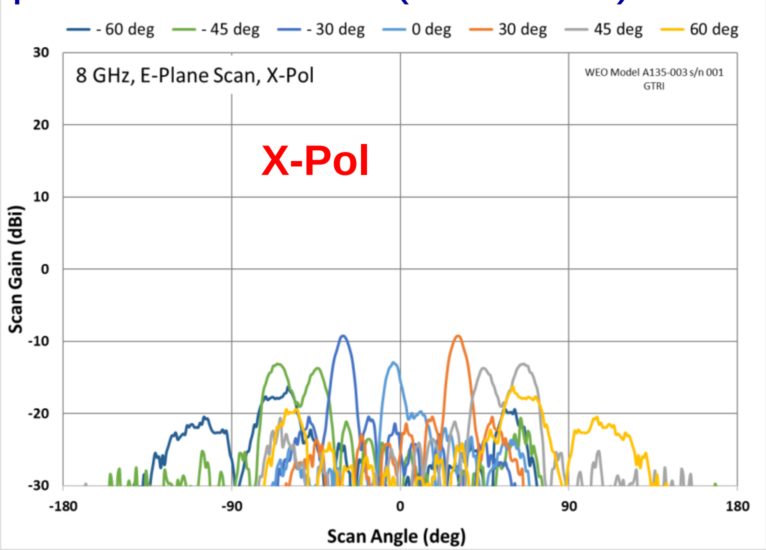


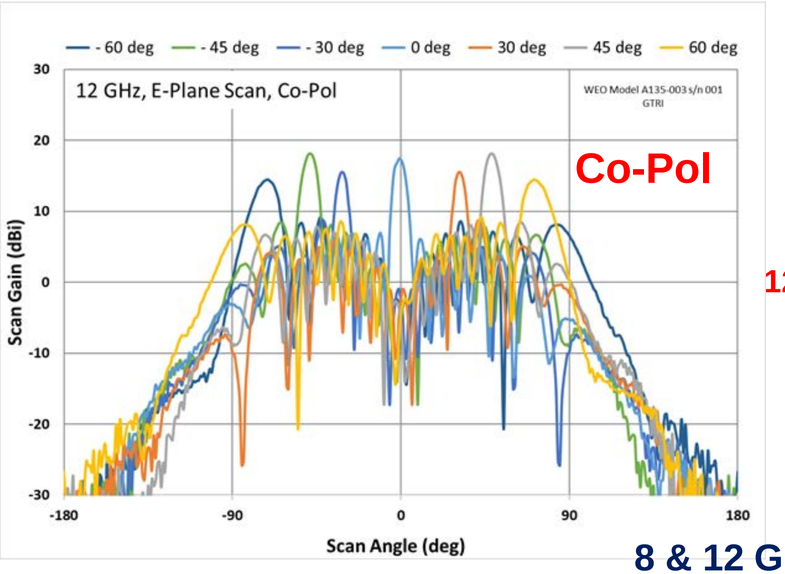
2 & 4 GHz, E-Plane

Measured array E-plane scan gain pattern 2-12 GHz (continued)

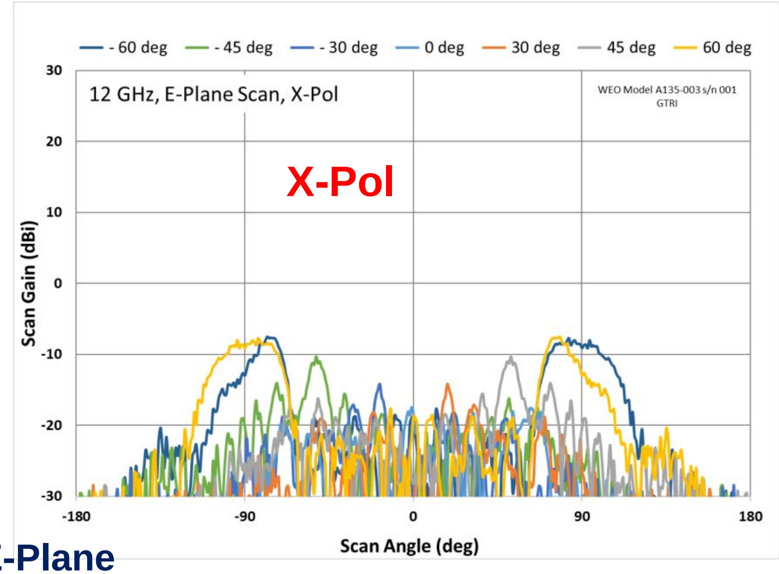


8 GHz



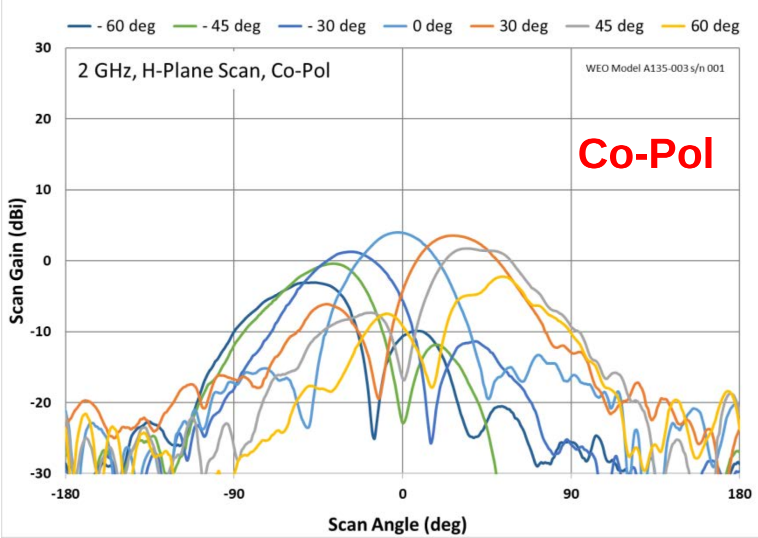


12 GHz

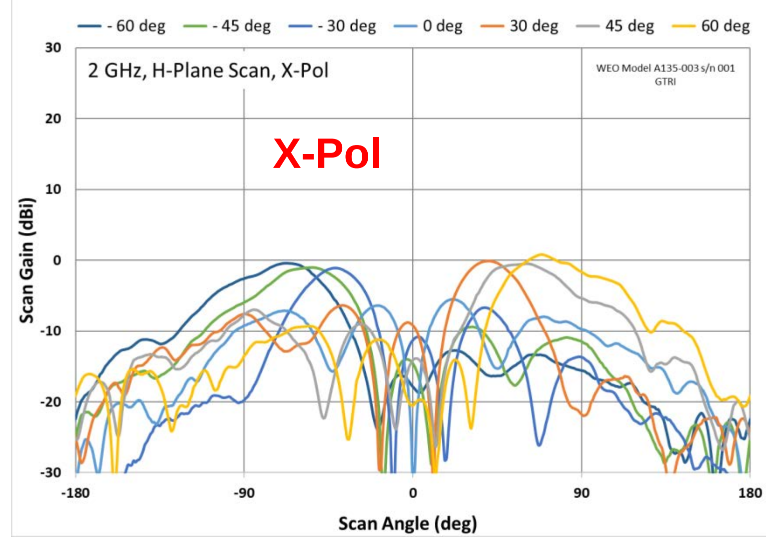


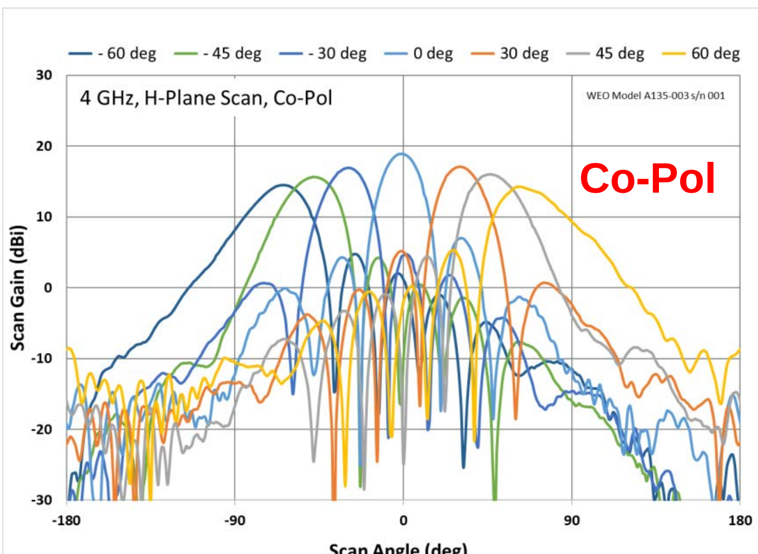
8 & 12 GHz, E-Plane

Measured array H-plane scan gain pattern 2-12 GHz

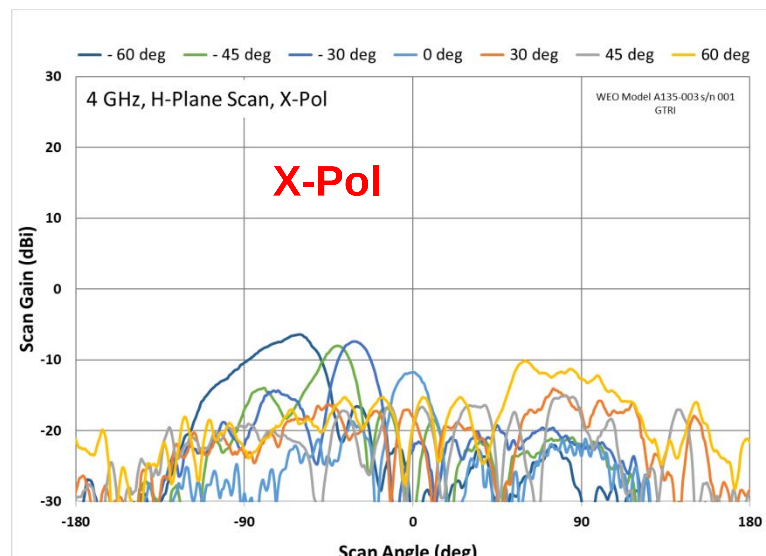


2 GHz



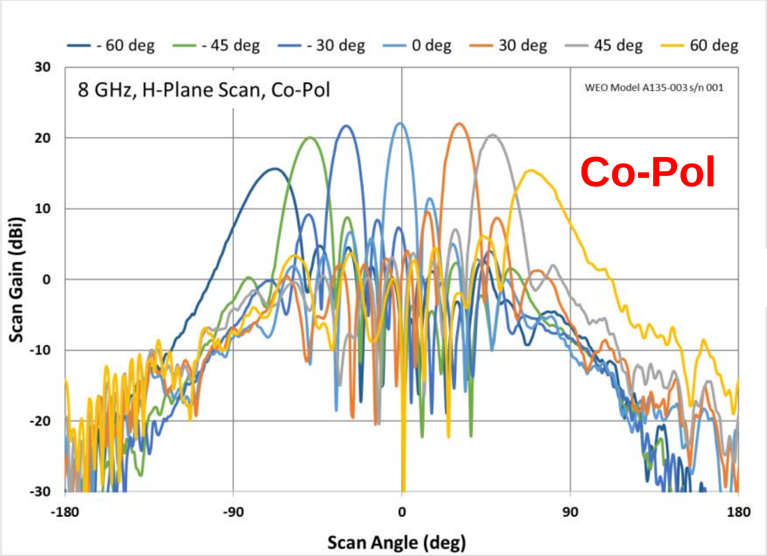


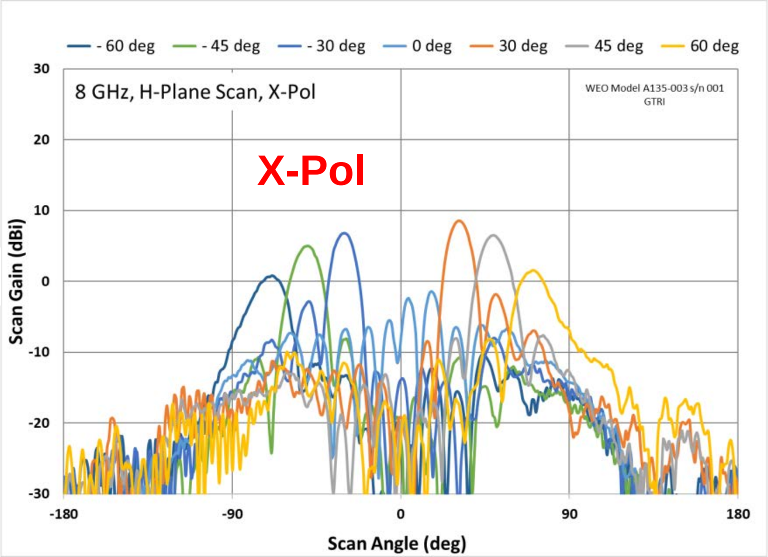
4 GHz



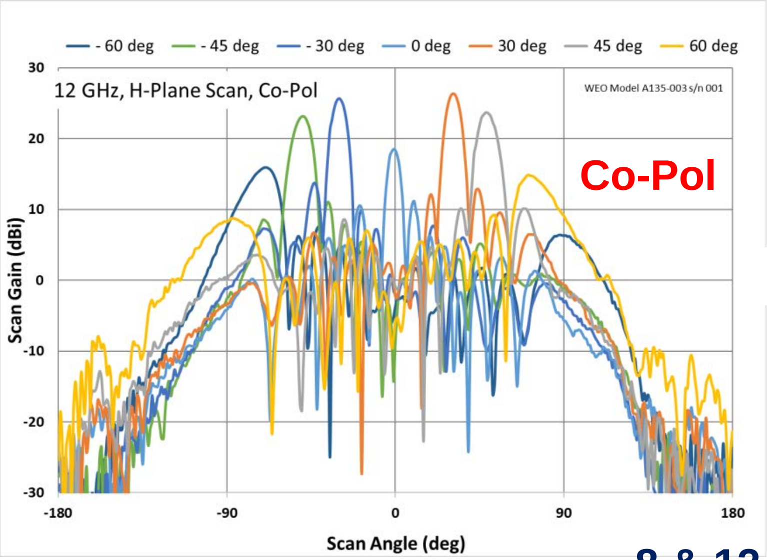
2 & 4 GHz, H-Plane

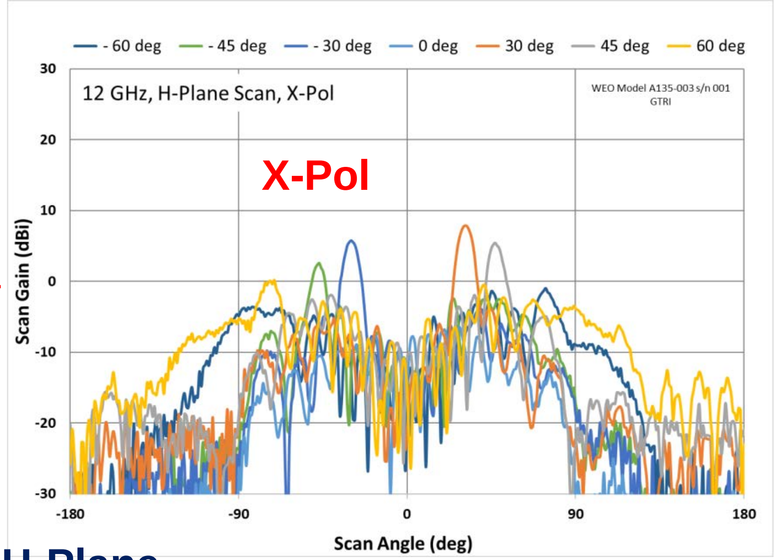
Measured array H-plane scan gain pattern 2-12 GHz (continued)





8 GHz

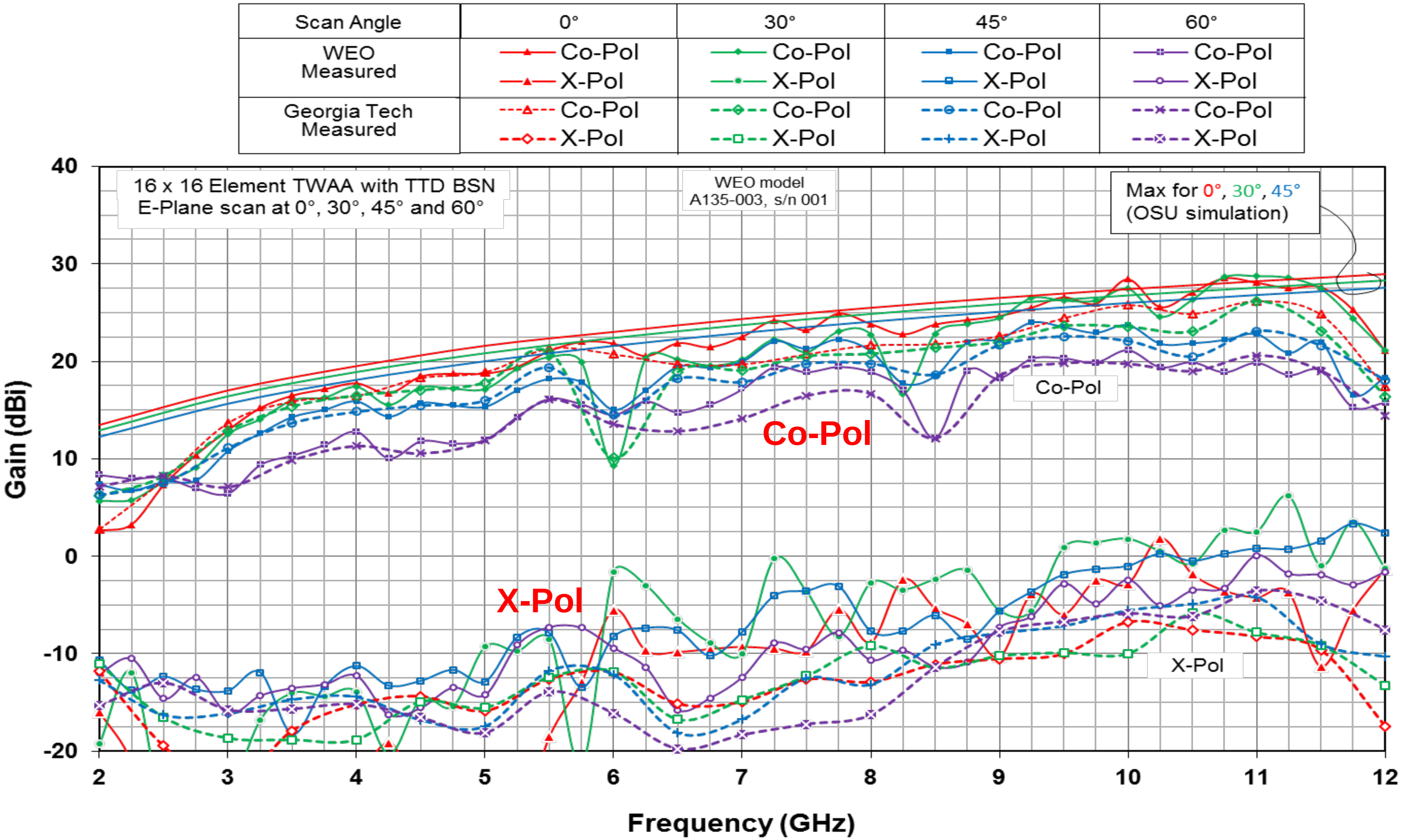




12 GHz

8 & 12 GHz, H-Plane

OSU simulation and measured data at GT (dash) and WEO (solid) for E-plane scan gain



Pitfalls of formulating MPPA as a scattering problem

- Formulating MPPA as a scattering problem has been a common practice in MPPA analysis and measurement (stemming from CSA's genetic mutation from radome for STEALTH application).
- However, antenna cannot be fully represented by a Thevinin's or Norton's equivalent circuit.
  - For example, a reflect array using broadband planar spiral element antenna claiming ultra-wide bandwidth, sponsored by many agencies during 1973-1982 as classified programs, began publically promoted without measured broadband data.
  - In 1981, this author pointed out the fatal flaw of the concept, which could not be wideband as claimed.

Wheeler's CSA has fatal shortcomings!

- Most MPPA approaches credited their concept to CSA.
- CSA's high X-pol problem is rooted in its incomplete mathematical formulation.
    - For completeness, both electric and magnetic currents are required to represent the equivalent sources on array surface.
- Implementation of CSA by treating each unit cell as a waveguide and then simplifying it by considering only the dominant propagating waveguide modes is valid only for a narrow bandwidth.

Heavy use of substrate/superstrate common in CSA adds modes, complicates boundary conditions!

- Use of dielectric and ferromagnetic substrates and superstrates leads to inhomogeneous medium. Mathematical formulation of the problem is thus complicated by the expanded differential equations, difficult to match their boundary conditions at interfaces between layers.
  - Thus the higher the difference in dielectric constants between adjacent layers, the more difficult to match the boundary conditions.

Concluding Remarks

- TWAA is shown to be capable of efficient wide scan up to 60° off broadside over 2-12 GHz (a 6:1 instantaneous bandwidth), not suffering from CSA's high X-polarization.
- Measurement using TTD in corporate feed configuration is a most rigorous and complete approach that is done first time for a large MPPA.
- After four prototypes using standard commercial PCB fabrication processes and commercial-off-the-shelf (COTS) parts and materials, TWAA has reached TRL-7 and MRL-7.
- Significant performance improvements can be achieved at the stage of integration to TR/RX.
- Pitfalls of the CSA approach have been discussed in this and previous papers.

Acknowledgment of contributions

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