BREAKTHROUGHS IN LOW-PROFILE LEAKY-WAVE HPM ANTENNAS

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19 Sept 2015

Data Item: A002 - Progress, Status, & Management Quarterly Report #8

Prepared for:

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ONR Code 30

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 19-09-2015	**2. REPORT TYPE** Quarterly	**3. DATES COVERED** *(From - To)* 18 Jun 2015 – 19 Sep 2015

4. TITLE AND SUBTITLE
Breakthroughs in Low-Profile Leaky-Wave HPM Antennas
Progress, Status, & Management Report
(Quarterly Report #8)

5a. CONTRACT NUMBER
N00014-13-C-0352

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Koslover, Robert, A.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Scientific Applications &
Research Associates, Inc.
6300 Gateway Drive
Cypress, CA 90630-4844

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Suite 1425
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
Code 30

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release; distribution is unlimited. Other requests for this document shall be referred to the Program Officer listed in the contract.

13. SUPPLEMENTARY NOTES
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14. ABSTRACT
This report describes progress during the 8th quarter of this program and summarizes the current status of the research. Technical activities this period included investigation and application of a simple but clarifying wave-mapping methodology that provides guidance in making more-effective use of curved platform surfaces. This results in conformal designs that provide both higher gain and greater peak power handling. In particular, this design perspective steered us to a notable success during this period, with the design of a CAWSEA that can deliver superior gain while conforming to the same radius cylinder as an earlier, standard/recommended design.

15. SUBJECT TERMS
Leaky-wave Antennas. High Power Microwaves (HPM) Antennas. Low-profile Conformal Antennas.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON (Monitor)** Lee Mastroianni
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	SAR	___	**19b. TELEPHONE NUMBER**(incl. area code) (703) 696-3073

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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1. INTRODUCTION

This is SARA's 8th Quarterly Report for "Breakthroughs in Low-profile Leaky-Wave HPM Antennas," a 37-month Basic Research effort sponsored by the US Office of Naval Research (ONR). This work includes fundamental theoretical analyses, numerical modeling, and related basic research. Objectives include to discover, identify, investigate, characterize, quantify, and document the performance, behavior, and design of innovative High Power Microwave (HPM, GW-class) antennas of the *forward-traveling*, *fast-wave*, *leaky-wave* class.

1.1. Overview of Previous Activities (1st thru 7th Quarter)

During the *first* quarter, we prepared and established useful equations and algorithms for predicting reflections and transmission of incident TE waves from parallel-wire grills, dielectric windows, and combinations of wire grills with dielectric windows, in problems reducible to purely H-plane (2D) representations. We then applied this theory to guide the design of high-gain configurations (again, limited to 2D, H-plane representations) for linear, forward traveling-wave, leaky-wave antennas. The theory built upon equivalent circuit methods and wave matrix theory, which provided useful formalisms upon which we continue to build.

During the *second* quarter, we pursued initial extensions of the previous work into three dimensions, in order to include phenomena with E-plane dependencies. We succeeded in adding into the wave-matrix formalism the reflection/transmission properties associated with the transition to free space from a *finite-width* leaky-wave channel, including the edge-tapering essential to HPM applications. These geometric aspects do not arise in analyses confined to the H-plane alone. Our 3D analyses were somewhat more reliant on numerical models than in the 2D analyses, due to the greater complexity of identifying and/or building practical analytic approaches capable of addressing true 3D geometries of interest.

During the *third* quarter, we explored channel-to-channel coupling (aka, mutual coupling) which (as we have noted earlier) is an important design concern, since it can impact antenna performance significantly in terms of gain, peak power-handling, and impedance matching. Our approach leveraged mostly numerical methods, along with some intuitive arguments, as we explored designs exhibiting different degrees of mutual coupling between adjacent channels. As past and current antenna literature attest, mutual coupling analyses are non-trivial; suffice to say, there is still much work to be done in this area.

During the *fourth* quarter, we continued to study and employ wave-matrix based methods, but with less success than before in applying this approach to *improve* or *optimize* the initial designs. The formalism itself is still valid, but offers reduced practical rewards once an *initial* (i.e., not fully-optimized) geometry (e.g., grill, window, channel depth, etc.) is derived from the more basic-level principles. At that stage, we are finding that further optimization is currently best proceeding via numerical means. Additional work in the fourth quarter led us to identify *new aperture geometries* of potentially-significant practical value, which included the "BAWSEA" and "GAWSEA". These configurations may significantly extend the utility of leaky-wave antenna technology to support integration on more challenging platforms.

During the *fifth* quarter, we designed, analyzed, and documented representative high-performance FAWSEA and CAWSEA antennas suitable for designation as "standard" or "recommended." The configurations we described were scalable with wavelength. These are the initial entries in a library of antennas that will continue to be built throughout this program.

During the *sixth* quarter, we performed additional investigation of designs to support the newer curved apertures, especially the "Bent Aperture Waveguide Sidewall-emitting Antenna" (BAWSEA). We presented this work at the 17th Annual Directed Energy Professional Society (DEPS) Symposium in Anaheim, CA, on March 4th, 2015. Our full slide presentation, entitled "Advances in Low-Profile Leaky-Wave Conformable Antennas for HPM Applications," was included in the unclassified proceedings CD that was recently distributed by DEPS to all the conference attendees.

During the *seventh* quarter, we investigated RAWSEA design considerations and showed that the angle of rotation between the leaky wave channels and the aperture can be understood in terms of an equivalent linear (non-rotated) displacement, an interpretation which helps to guide application of the wave-matrix formalism. However, more work is still needed to speed-up the RAWSEA design process.

For more information, we encourage the reader to refer our earlier *Quarterly Reports #1* thru *#7.*

1.2. Overview of Recent Activities (8th Quarter)

Much of our work this quarter involved exploring ways to apply the geometric flexibility of low-profile leaky-wave antennas toward more-effective use of curved platform surfaces. We are pleased to report that it now appears possible, in at least some important cases, to make even better use of curved platform surfaces than we expected, and in ways that designers might not initially appreciate. Recall that the concept of the "Generalized Aperture Waveguide Sidewall-Emitting Antenna" (GAWSEA) embraces simultaneous curvatures (albeit, with some limitations) about three axes, as well as beneficial use of multiple connected and/or disconnected apertures. This implies that the designer's perspective should be expanded and become more platform-centric, than before. To clarify:

"Antenna-centric" question sequence:

- What surface-conformal aperture geometries are realizable via this technology?
- Which one(s) in that list, if any, can provide the HPRF performance that I need?
- Will it fit into my platform?

"Platform-centric" question sequence:

- What aperture-field distribution(s) on my curved-surface platform, if any, can provide the HPRF performance that I need?
- Can a forward traveling-wave, leaky-wave type antenna deliver that kind of distribution(s)?
- Will it fit into my platform?

Of course, for a single, flat, rectangular aperture, the choice of traveling-wave aperture field *distribution* is simple – uniform magnitude, polarization, and linear-phase are generally best, preferably with the electric field oriented across the shorter dimension of the aperture. But what about a cylindrical surface or the surface of an ogive? We have noted methods previously for compensating for the phase-errors introduced when using curved aperture surfaces, specifically in the context of managing separate curvatures about each of three axes, labeled variously as "curved" in the E-plane (CAWSEA), "arched" in the H-plane (AAWSEA), and "bent" about the normal to the aperture plane (BAWSEA). But: (1) these were not general treatments, since each curvature was considered separately, and (2) the potential benefit, if any, of an aperture with a deliberately *non-uniform* magnitude field distribution was not considered. A more in-depth discussion of this is provided in Section 3.

Another activity pursued this quarter was the continued development (see our previous report) of an improved and more general circuit model for a flared (curved-edge) aperture, which would be particularly (but not exclusively) useful in optimizing RAWSEA configurations. Prof. Deborah Koslover (Dept. of Mathematics, Univ. of Texas at Tyler) has been (at no cost to ONR) gathering, evaluating, and preparing a set of analytic tools to attack this problem, inspired by the techniques employed by Marcuvitz [1951] and Schwinger [1968]. The first step is to reproduce the results (either the equivalent circuit elements or the complex transmission and reflection coefficients) for the 90°-edged aperture already appearing in the *Waveguide Handbook*, then generalize the proven technique to the curved-edge case, which is of much greater interest to us. Her initial approach is based on conformal mapping. It has not yet reached the stage where we have specific results to report here; we will return to this subject in our next report.

Further information about our recent research activities is provided in Section 3.

1.3. Upcoming conferences

For future reference, we note that there are at least two upcoming conferences where public presentation of results from this research may be appropriate. The first is the DEPS 18th Annual Directed Energy Symposium, Albuquerque, NM, March 7-11, 2016 (http://www.deps.org/DEPSpages/DEsymp16.html). As of this writing, the DEPS Call for Papers has not yet been posted. The second is the IEEE AP-S/USNC-URSI conference to be held June 25-July 1, 2016, in Puerto Rico (see http://www.2016apsursi.org/CallForPapers.asp). The paper submission deadline for that conference is Jan. 18, 2016.

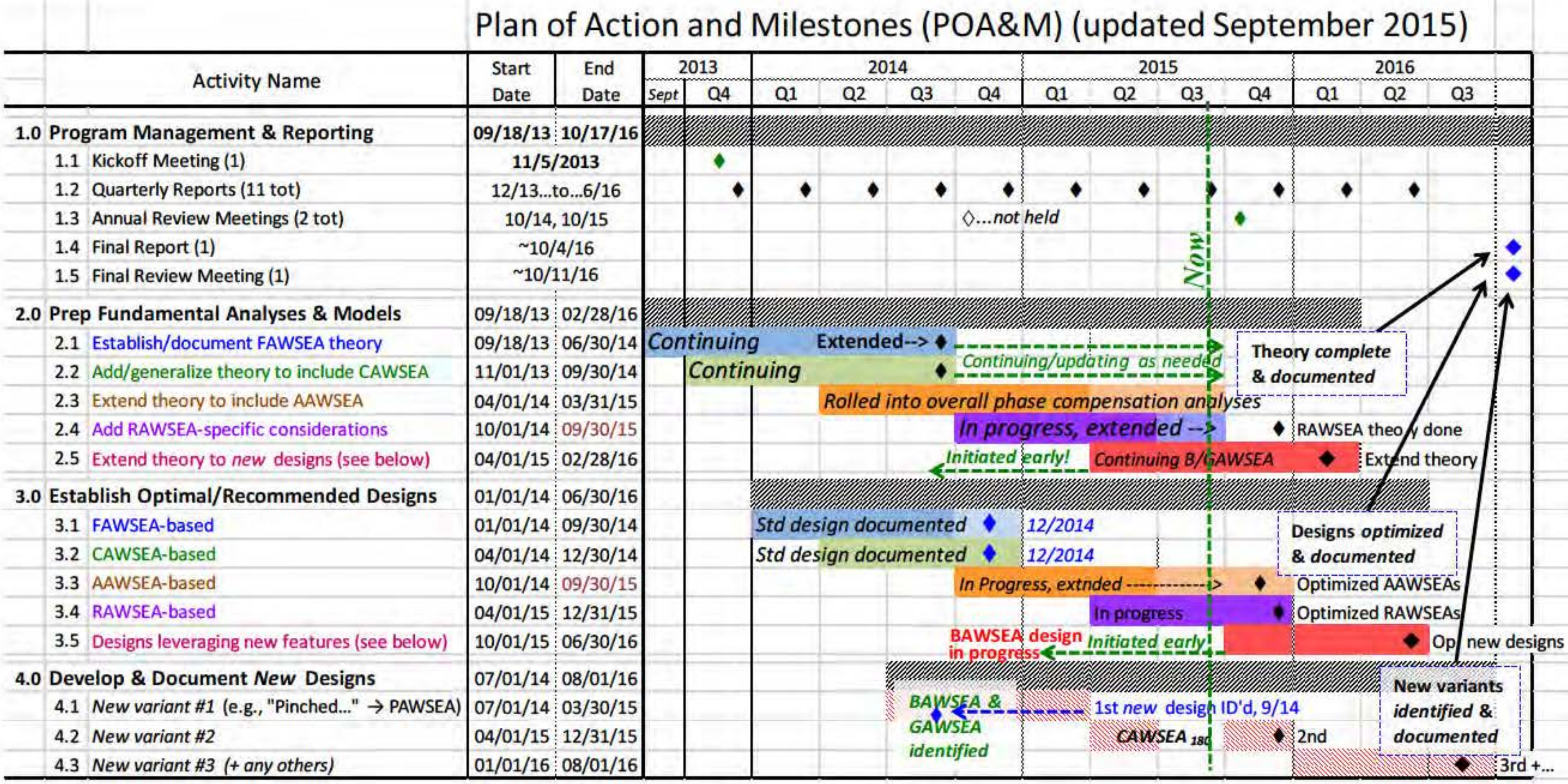
2. STATUS OF THE PLAN/SCHEDULE AND FUNDING

Figure 1 (next page) ~maps out the updated program plan, for quick reference.

As in prior reporting periods, we have made some adjustments. We now treat theoretical analyses of the AAWSEA as a task falling within the more generalized framework for leaky-wave-driven curved aperture-surfaces, which includes all the individual curvatures (CAWSEA, AAWSEA, and BAWSEA) and combinations thereof (such as the “pinched” PAWSEA, to conform to a tangent ogive). In contrast, and as noted before, the RAWSEA’s unique rotation of the guides relative to the aperture introduces its own distinct issues, whether implemented in combination with a flat, singly-, or multiply-curved aperture.

The subject contract was awarded on 9/18/2013 and has an end date of 10/17/2016. The total contract value is $868,350, with current (per P00005 signed on 3/17/2015) allotted funding of $780,473. According to SARA’s accounting system, as of Sept. 11, 2015, expenses and commitments (including fee) totaled $517,452, thus leaving $263,021 available, as of that date. If one simply compares the calendar and spending on this project, we have consumed ~65% of the calendar and ~60% of the total contract value. We thank ONR for the continued support of this project.

There are no technical, schedule, or other funding-related program problems/concerns to report at this time.



Plan of Action and Milestones (POA&M) (updated September 2015)

	Activity Name	Start Date	End Date
1.0	**Program Management & Reporting**	**09/18/13**	**10/17/16**
1.1	Kickoff Meeting (1)	11/5/2013	
1.2	Quarterly Reports (11 tot)	12/13...to...6/16	
1.3	Annual Review Meetings (2 tot)	10/14, 10/15	
1.4	Final Report (1)	~10/4/16	
1.5	Final Review Meeting (1)	~10/11/16	
2.0	**Prep Fundamental Analyses & Models**	09/18/13	02/28/16
2.1	Establish/document FAWSEA theory	09/18/13	06/30/14
2.2	Add/generalize theory to include CAWSEA	11/01/13	09/30/14
2.3	Extend theory to include AAWSEA	04/01/14	03/31/15
2.4	Add RAWSEA-specific considerations	10/01/14	09/30/15
2.5	Extend theory to *new* designs (see below)	04/01/15	02/28/16
3.0	**Establish Optimal/Recommended Designs**	01/01/14	06/30/16
3.1	FAWSEA-based	01/01/14	09/30/14
3.2	CAWSEA-based	04/01/14	12/30/14
3.3	AAWSEA-based	10/01/14	09/30/15
3.4	RAWSEA-based	04/01/15	12/31/15
3.5	Designs leveraging new features (see below)	10/01/15	06/30/16
4.0	**Develop & Document *New* Designs**	07/01/14	08/01/16
4.1	*New variant #1* (e.g., "Pinched..." → PAWSEA)	07/01/14	03/30/15
4.2	*New variant #2*	04/01/15	12/31/15
4.3	*New variant #3 (+ any others)*	01/01/16	08/01/16

Figure 1. Updated Program Plan

3. RESEARCH AND ACTIVITIES PERFORMED THIS PERIOD

3.1. Curved-surface Aperture Fields that Achieve High-gain HPRF Performance

The highest peak power-handling in any leaky-wave aperture, or most other apertures, is generally realized with the most uniform-magnitude distribution of the aperture electric field. For a flat aperture, this also generally yields the most gain, provided that a linear-phase distribution is maintained. For a curved aperture (e.g., cylinder, ogive, etc.), some radiating portions are necessarily oriented in different directions than optimal. As an extreme example, there would not seem to be much point in distributing HPRF power to *shadowed* surface regions (i.e., platform surfaces with their lines-of-sight to the target totally blocked, either by the platform itself or by other objects). *The more interesting question here concerns the utility, if any, of platform surfaces that are neither shadowed nor particularly well-oriented.* Our prior investigations (most notably, in preparing our standard CAWSEA design) simply ignored the use of aperture surfaces whose surface-normals veered away from the target direction by more than ~45°. Though naïvely/intuitively reasonable, this limitation was not theoretically justified. From an "antenna-centric" design perspective, it makes good sense to pursue the most aperture-efficient antennas. But from a "platform-centric" perspective (as noted earlier in this report), a more appropriate objective is to make the best use of the platform's surface to maximize both gain and peak power handling, since it is these factors (aside from any limitations of the HPRF source and its supporting subsystems) that ultimately constrain the maximum power density deliverable to distant targets. In particular, an antenna configuration delivering a *reduced* aperture efficiency, but which utilizes a *significantly greater fraction* of a curved-platform's surface, may actually be able to deliver a greater overall power density on a target than a more efficient antenna, if the latter fails to take good advantage of the platform's available surface.

To better understand how to proceed, we will consider here some examples of simplified representative platform shapes and apply analytic aperture fields with phases that match the desired radiating plane waves. *Ideally*, we would like to fully-match our platform's aperture surface fields (in terms of direction, amplitude, and phase) to a plane wave, however we are generally constrained (and this is not the only constraint) to choose fields that are *tangent* to the aperture surface. The simplest way to obey this constraint is to do a vector projection of the wave onto the surface. For an aperture surface with a local surface-normal $\hat{n}$, we can simply subtract the normal component of E from the desired plane wave:

$$\vec{E}_{ap} = \vec{E}_{pl} - \hat{n}\left(\hat{n} \cdot \vec{E}_{pl}\right),$$

i.e., $\vec{E}_{ap}$ is the component of $\vec{E}_{pl}$ that is tangent to the surface. One consequence of this approach is that for all of the surface, $\left|\vec{E}_{ap}\right| \le \left|\vec{E}_{pl}\right|$. This *magnitude-reducing* mapping puts the strongest E fields in locations where the surface is intuitively best-oriented for launching the desired wave, but weaker fields where the surface would seem to be less-advantageously oriented. Alternatively, we can eliminate that scaling altogether, as follows:

$$\vec{E}_{ap} = \frac{\vec{E}_{pl} - \hat{n}\left(\hat{n} \cdot \vec{E}_{pl}\right)}{\left|\vec{E}_{pl} - \hat{n}\left(\hat{n} \cdot \vec{E}_{pl}\right)\right|} E_0$$

This is a *magnitude-preserving* projection, i.e., $\left|\vec{E}_{ap}\right| = \left|\vec{E}_{pl}\right|$. An immediately-appealing feature of this second mapping option is the expectation of it maximizing peak-power handling. But we should mention that there also exists at least one more option, which is essentially a *reverse* projection. This follows from demanding that *any* surface field of a contributing aperture region carry a tangent field that would yield the plane wave, if that field were projected into the transverse plane of the desired wave. This scales the aperture fields *oppositely* to that of the direct projection case, yielding the following mapping expression:

$$\vec{E}_{ap} = \frac{\vec{E}_{pl} - \hat{n}\left(\hat{n}\cdot\vec{E}_{pl}\right)}{\left|\vec{E}_{pl} - \hat{n}\left(\hat{n}\cdot\vec{E}_{pl}\right)\right|^2} E_0$$

This third case is a *magnitude-increasing* projection, i.e., $\left|\vec{E}_{ap}\right| \geq \left|\vec{E}_{pl}\right|$. Its intuitive (but naïve) appeal is that it endeavors to force the local aperture *E* field to generate the desired plane wave point by point. But this is regardless of whether it generates strong (or stronger) radiating waves in other directions as well, and also leads to potentially-extreme local aperture field strengths. We include it here primarily for completeness, but will not study it in more detail in this report.

Now, for simplicity let us assume, without loss of generality, that the *desired* plane wave is given by:

$$\vec{E}_{pl} = \hat{y}E_0 \exp(-jk_0 z)$$

For this particular $\vec{E}_{pl}$, the above three expressions become (after just a little algebra):

Direct Projection:	$\vec{E}_{ap} = \left(-n_x n_y \hat{x} + \left(1-n_y^2\right)\hat{y} - n_z n_y \hat{z}\right)E_0 \exp(-jk_0 z)$
Mag-preserving Projection:	$\vec{E}_{ap} = \frac{\left(-n_x n_y \hat{x} + \left(1-n_y^2\right)\hat{y} - n_z n_y \hat{z}\right)}{\sqrt{\left(n_x n_y\right)^2 + \left(1-n_y^2\right)^2 + \left(n_z n_y\right)^2}} E_0 \exp(-jk_0 z)$
Mag-enhancing Projection:	$\vec{E}_{ap} = \frac{\left(-n_x n_y \hat{x} + \left(1-n_y^2\right)\hat{y} - n_z n_y \hat{z}\right)}{\left(n_x n_y\right)^2 + \left(1-n_y^2\right)^2 + \left(n_z n_y\right)^2} E_0 \exp(-jk_0 z)$

The expressions shown above support convenient representations in Comsol Multiphysics. Figure 2 shows a few examples of simple curved surfaces, along with plots of mapped fields based on the *direct* and *magnitude-preserving* transformations, since we regard these mappings to be of primary interest. The examples include: (1) a 1m-long cylinder with a 25cm radius, with its axis 60° relative to k_0; (2) a sphere with a 25cm radius; and (3) a 75cm-long cylinder with a 25 cm radius, extended by a 75cm-long tangent ogive, with their common axis oriented 60° relative to k_0. Snapshots in Figure 2 are all for f= 1.0 GHz.

Once we have quantified the mapped aperture fields, it is relatively straightforward to compute the far-field patterns and gain that these distributions (if realized) would generate. In Figure 3, we compare the predicted gains for the examples in Figure 2, across a 3-to-1 range of frequencies. Most interestingly, in all three examples and at all frequencies, the *magnitude-preserving* wave projections yielded higher gains. It was not obvious to us in advance that this would be the case, but it is a very welcome result, since (as noted earlier) this type of aperture illumination should also provide ~optimal peak power-handling.

The noticeable improvement in gain due to better-utilization of the non-shadowed half of the cylinder (see top rows of Figure 2 and Figure 3) suggests that our recommended/standard CAWSEA design for a cylindrical platform is not taking full advantage of the available[1] surface. So let's revisit that design.

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[1] In practice, integration of other platform hardware, including waveguide plumbing, may also limit aperture sizes. But it is still valuable to understand limits imposed by the platform exterior, independent of other packaging issues.

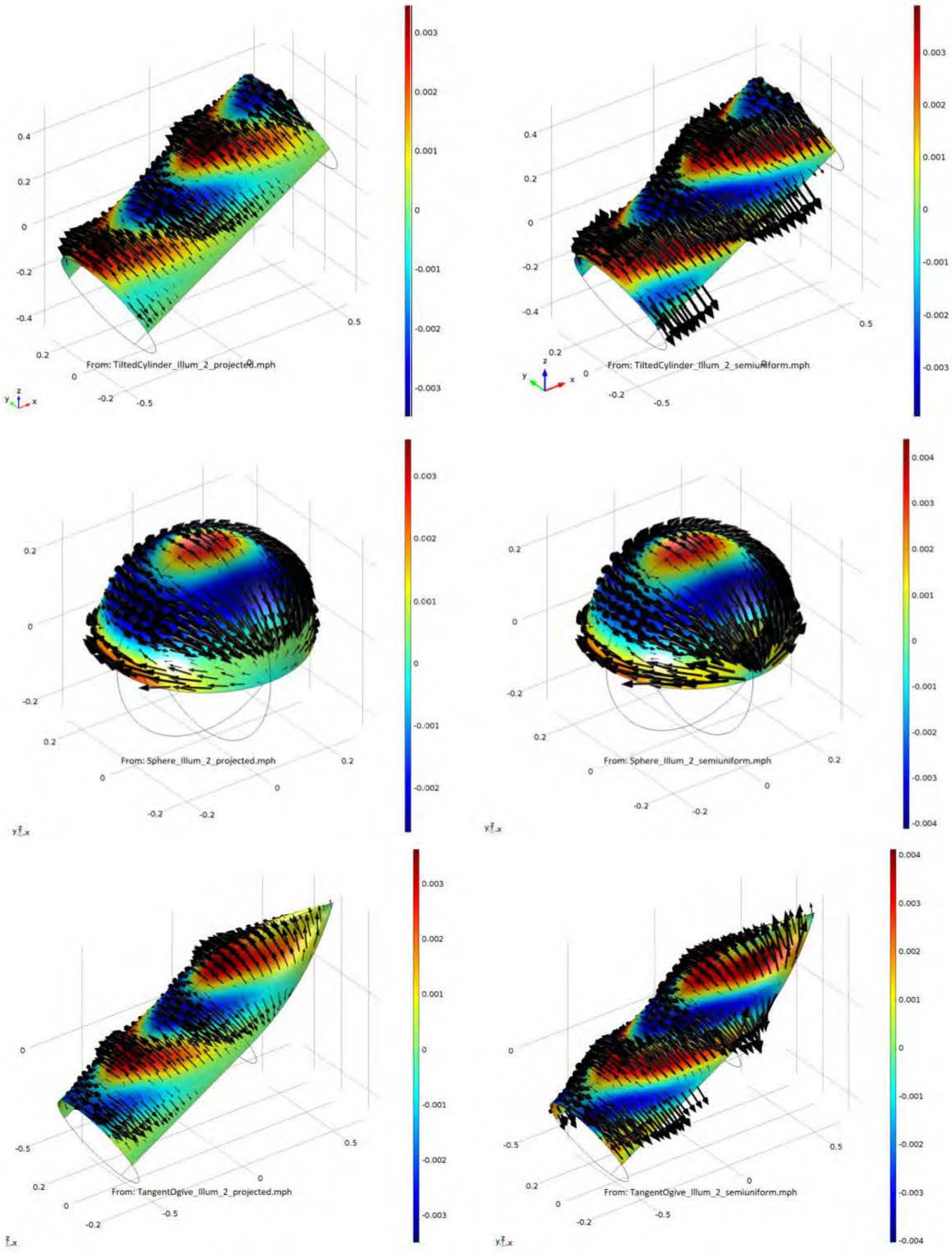


Figure 2. Snapshots of projected plane-waves onto a cylinder, sphere, and cylinder + ogive. Left column: *Direct* projection. Right Column: *Magnitude-preserving* projection. Arrows: Electric field. Colors: H_x (reveals the phase). $f=f_0$ (1 GHz).

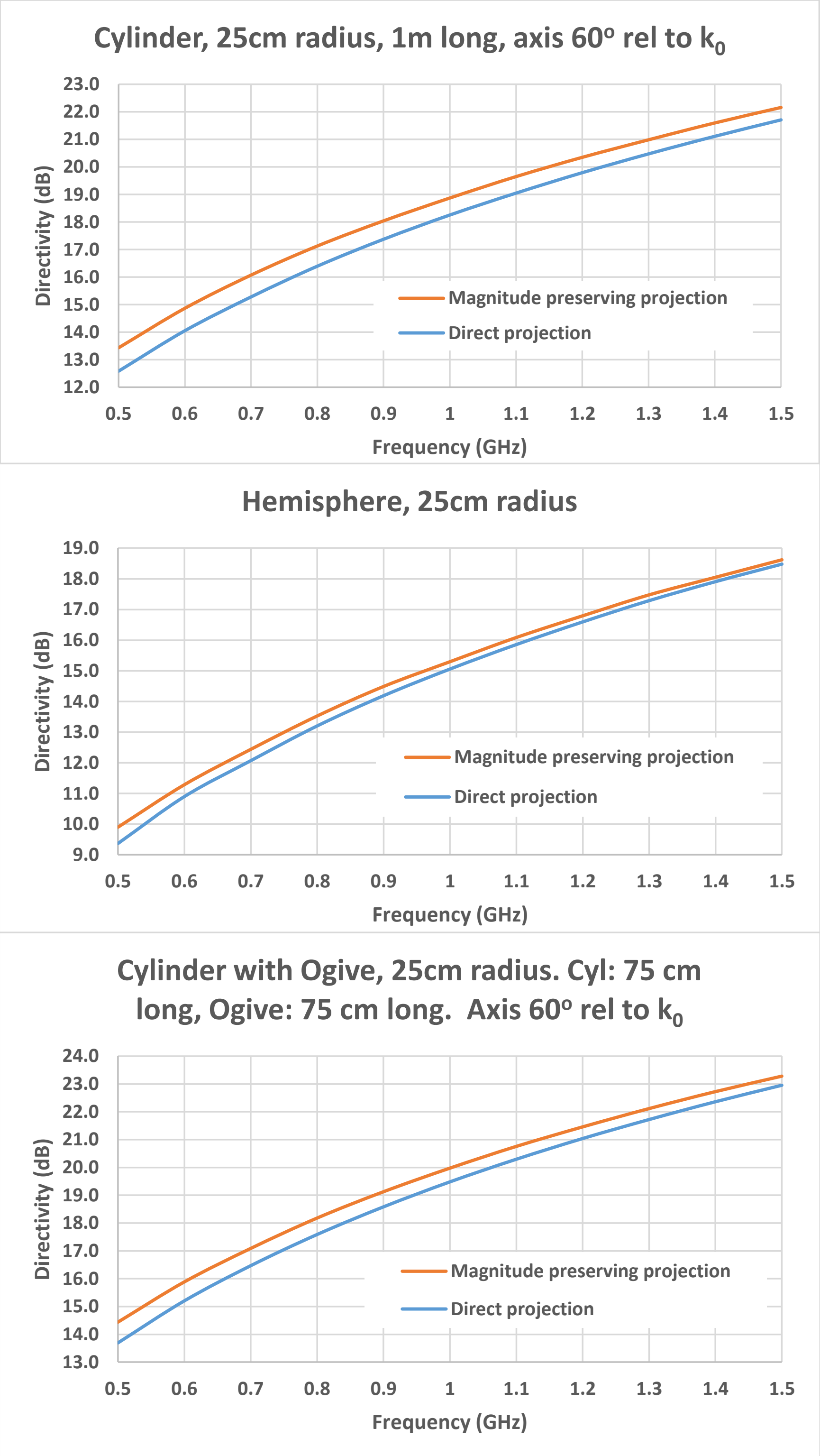
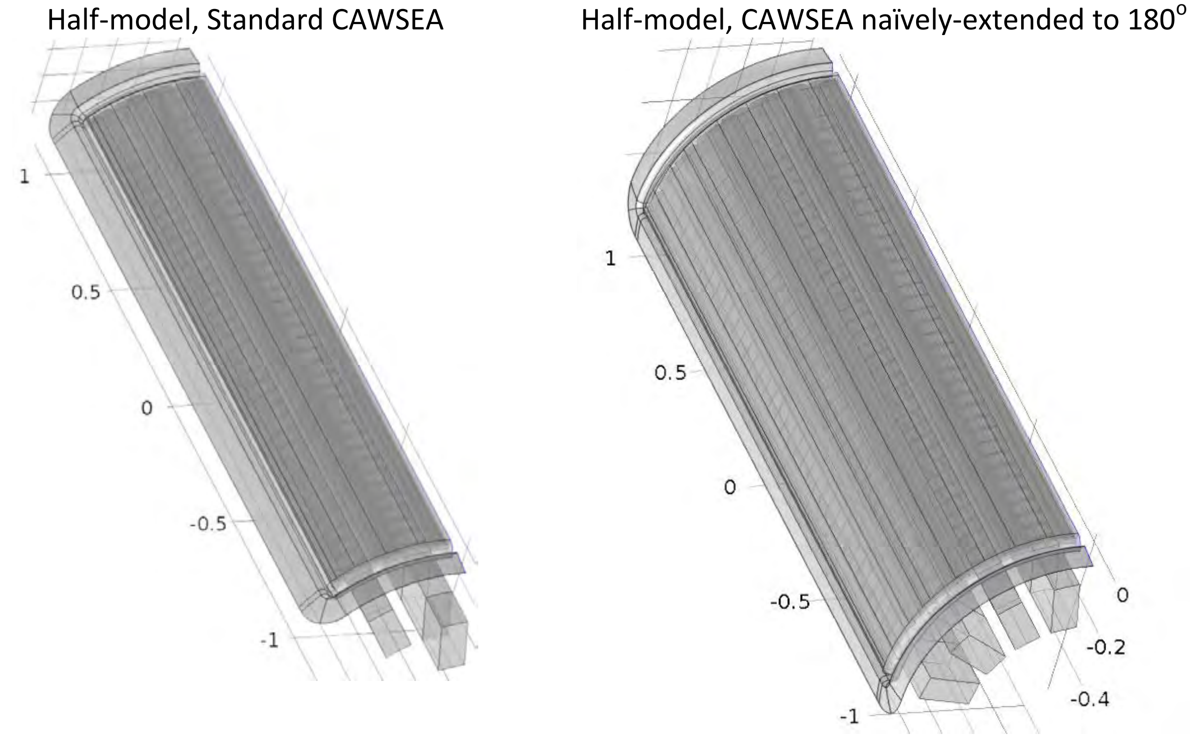


Figure 3. Predicted gains vs. frequency, computed using the projected aperture fields on the example surfaces in Figure 2.

3.2. A Higher-gain CAWSEA.

In light of the results in the top-row of Figure 3, consider extending the cross-sectional arc-length of our standard/recommended CAWSEA design (aperture wraps 90° azimuthally) to a full 180° wrap. The *simplest* way to attempt to do this is to add more channels, in a manner such as shown in Figure 4.

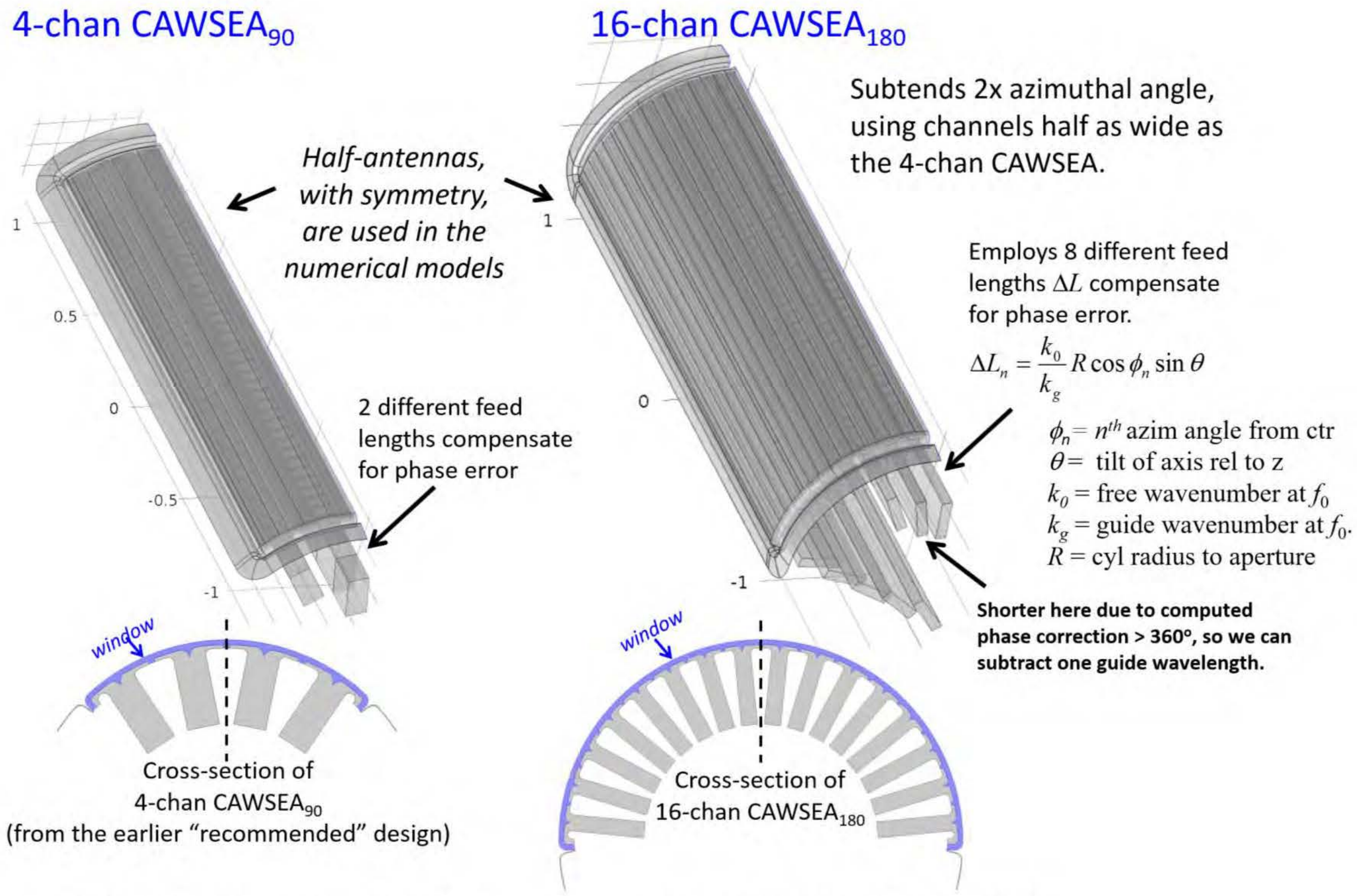

Half-model, Standard CAWSEA

Half-model, CAWSEA naïvely-extended to 180°

Figure 4. Naïve extension of our standard CAWSEA design (left) to a full 180° half-cylinder. (Half models are shown above, using symmetry). Phase-correcting feeds are not shown in the right-hand panel, but phase-correction was investigated (see text).

To cut to the chase, this initial approach *failed*. The aperture-phase correction required in the standard CAWSEA (which we shall now refer to as a "4-chan CAWSEA_{90}") is sufficiently minor that it can be moderately-approximated via the channel-discretization shown above/left. But that approximation fails for the aperture on the right in Figure 4; there does not appear to be any way to phase these eight discrete channels (four in each half) to compensate adequately. Regardless of feed phasing, the gain resulting from this aperture is actually *less,* despite its 2x-larger physical surface area.

Fortunately, there is a solution. Figure 5 shows a preliminary version of a 16-chan CAWSEA_{180}, where we employ channels half as wide and twice as densely-packed as in the 4-chan CAWSEA_{90}. Grill wire sizes and spacings in the narrower channels were unchanged (not re-optimized), to reduce the design time for this configuration. The close-packing of channels suffers from increased cross-channel coupling and VSWR, but our purpose with this model was merely to see if we could find a buildable configuration with enhanced performance (more gain, in this case) relative to the earlier design, yet conform to the same diameter cylinder. The simple channel layout in Figure 4 failed in that regard, but the layout in Figure 5 is a success worthy of additional study and optimization. Since the phase corrections required in the feeds are large, and optimized for only one frequency, a design like this offers reduced bandwidth (e.g., +/- 5% vs. +/- 10%) compared to the earlier design, but could still be adequate for use with many HPM sources.

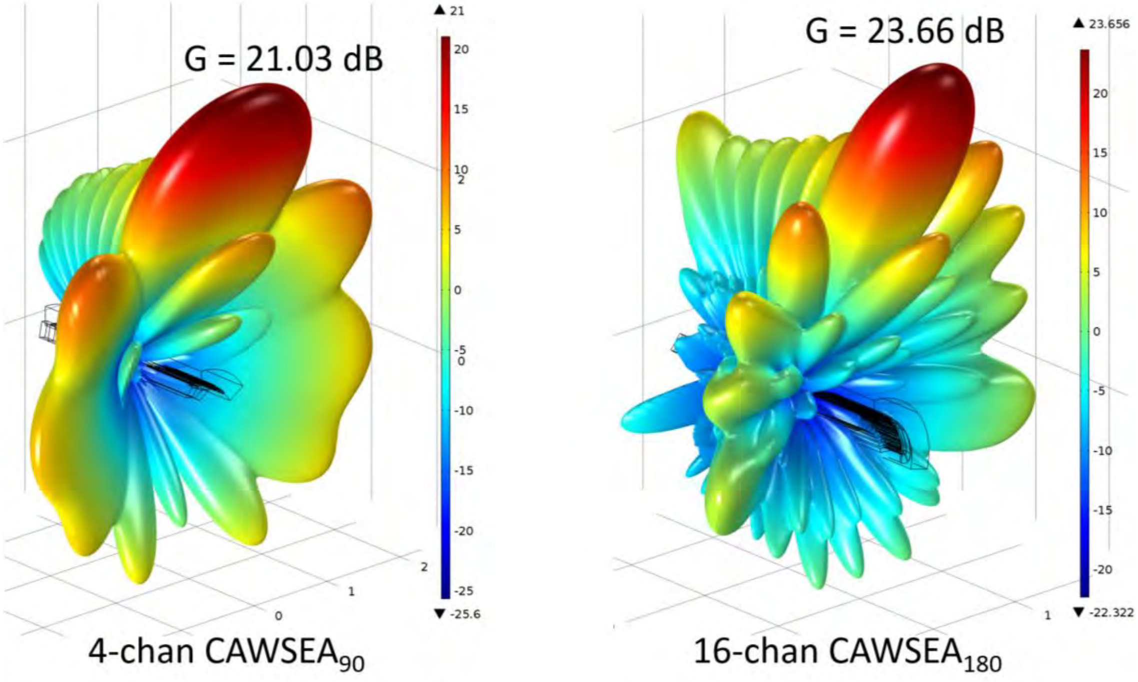


From: FourChan_Std_CAWSEA_5e_Optfor1GHz_phdelayed.mph

From: Rev2_ThinChan_CAWSEA_180_comp_phased.mph

Figure 5. Geometry comparison of the "standard" 4-chan CAWSEA$_{90}$ and a new (preliminary) 16-chan CAWSEA$_{180}$

Figure 6 compares computed 3D gain patterns at $f=f_0$ (1 GHz). The 16-chan CAWSEA$_{180}$ delivers about 2.6 dB more gain, which is a *major improvement* (i.e., >80% more power density on a distant target, for a given source power). The E-plane pattern is narrower, corresponding to the higher gain. There is a more prominent, but not too severe, rear sidelobe due to greater reflections (a reversed-direction traveling wave) from the termination end. We suspect this reflection can be reduced via some design adjustments.



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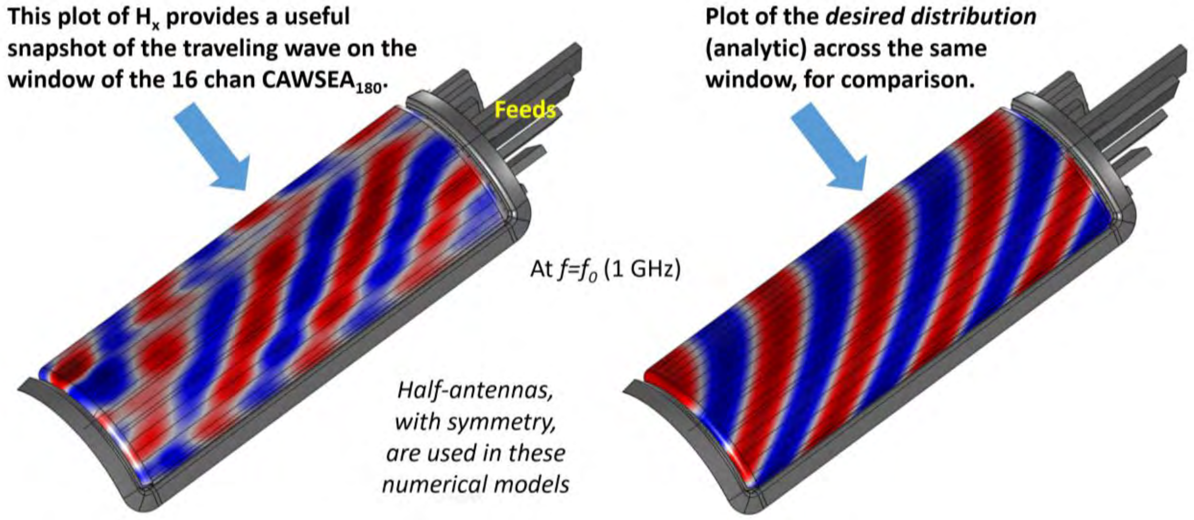
From: Rev2_ThinChan_CAWSEA_180_comp_phased.mph

Figure 6. 3D gain patterns at f=1.0 GHz. Phase-compensated CAWSEAs.
(RF model outlines are included in the images, to clarify the antenna orientation.)

Figure 7 compares the computed achieved aperture phase distribution vs. the desired one. There is clearly room for improvement in several places, but the aperture distribution overall is a fair match.



This plot of H_x provides a useful snapshot of the traveling wave on the window of the 16 chan CAWSEA$_{180}$.

Plot of the *desired distribution* (analytic) across the same window, for comparison.

At $f=f_0$ (1 GHz)

Half-antennas, with symmetry, are used in these numerical models

Figure 7. Left: Aperture distribution computed from 3D RF model of 16-chan CAWSEA$_{180}$.
Right: Distribution from an ideal magnitude-preserving plane wave projection.

Figure 8 summarizes some of the more important predicted performance characteristics vs frequency. Note especially the improvement in gain.

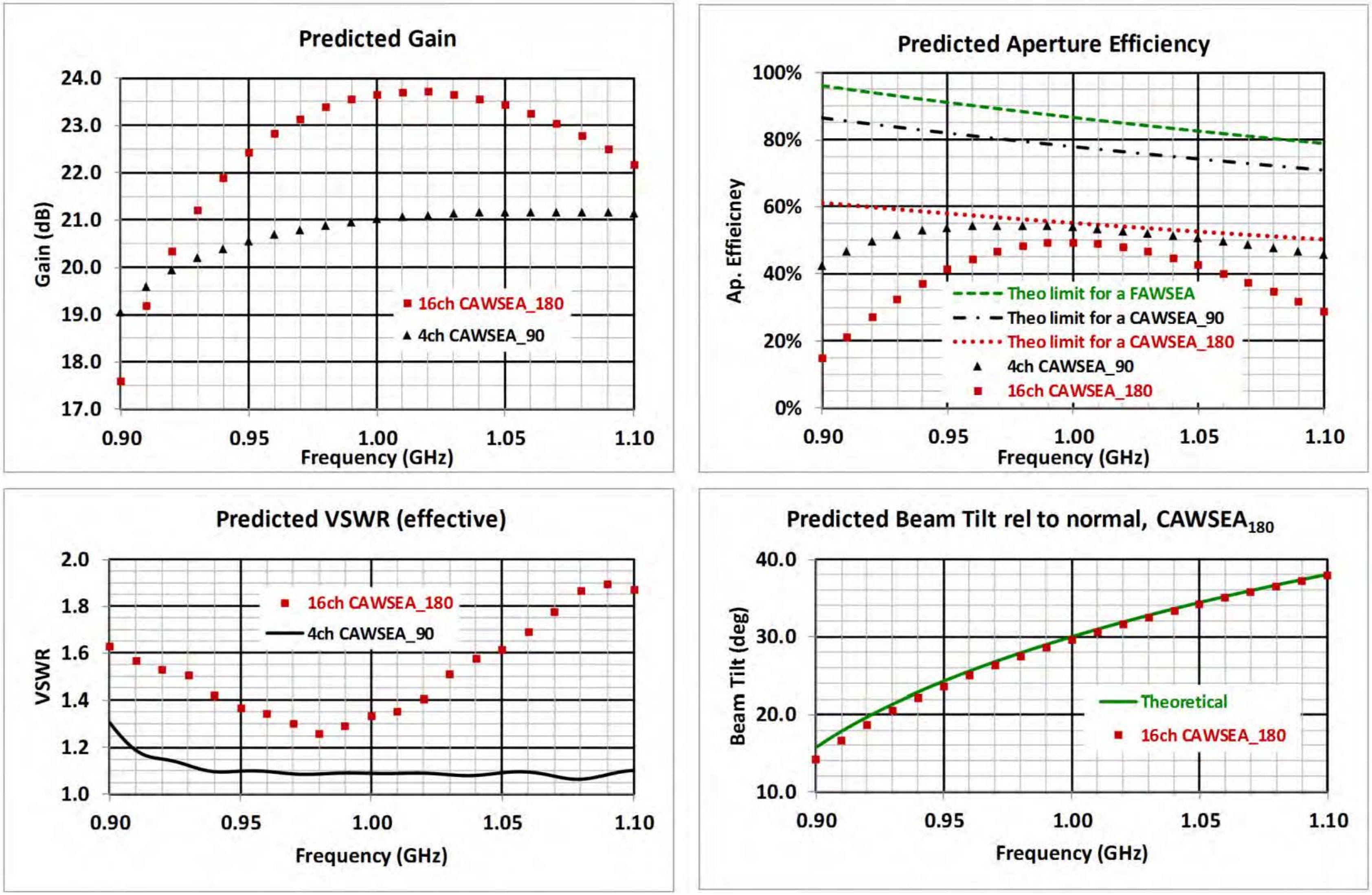


Figure 8. Summary and comparisons of gain, aperture efficiency, VSWR, and beam-tilt vs frequency.

4. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

Research performed during this 8th quarter of the R&D program investigated a new design perspective, which we formulated to guide us in making more-effective use of curved platform surfaces, leveraging the opportunities provided by the geometric flexibility of forward traveling-wave leaky-wave antennas. Our identification of a potentially-useful and substantially higher-gain CAWSEA configuration represents an encouraging payoff from this thought-process. We expect to continue to employ this approach in investigating other curved surfaces.

In addition, we are continuing to develop and expand our standard designs library and to refine our design algorithms/scripts. We look forward to improving the designs established so far and are documenting them to enable use and reference by other antenna designers.

As always, we appreciate ONR's continuing support for this R&D.

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