Investigations on the Volcano Smoke Antenna

Lee Paulsen, James B. West Member, IEEE., W. F. Perger, Member, IEEE., J. Kraus, Fellow, IEEE

Abstract—With the contemporary need for broad-band antennas in digital communications, the volcano smoke antenna (VSA), originally proposed by J. Kraus in the 1940s, has been investigated using current instrumentation and modeling software. A bandwidth of at least 10 to 1 is shown for both the voltage-standing wave ratio (VSWR) and antenna far-field pattern. A detailed comparison between the numerical simulations and experiment over the frequency range of 800 MHz to 15 GHz is presented and excellent agreement observed.

I. INTRODUCTION

The Volcano Smoke Antenna
By John Kraus

In 1945 at the Harvard University Radio Research Laboratory, I was developing broadband direction-finding antennas. Inspired by the broadband ideas of my group leader, Andrew Alford, I constructed a 20-cm tall antenna of the type shown in the sketch of Fig. 1. I made the bulb and curved ground plane out of modeling clay and coated it with silver paint. It had a very low VSWR over a very wide bandwidth and when I showed the model to Alford, he said, “Oh, volcano smoke!” And “volcano smoke” it has been ever since.

Fig. 1. Cut-away view of the volcano smoke antenna.

In this article Prof. Warren Perger and his students, in collaboration with Rockwell-Collins, Inc., analyze the shape-performance characteristics quantitatively with the objective of determining the optimum shape. This is an interesting challenge because the antenna by its very nature is an extremely non-critical structure.

With the advent of modern digital spread-spectrum communication techniques, the need for higher-bandwidth antennas has correspondingly grown. Traditional approaches to the problem of developing wide-band antennas have included the log-periodic dipoles [1], conical and planar spirals [2], and linearly tapered bodies of revolution (the bicone [3] and v-conical [4] being examples). More recently, research has been focused in the realm of linear tapered slot antennas (LTSA) [5], fractal antennas [6], and the Vivaldi [7–10]. These modern devices have the advantage of being relatively easily constructed for operation at high frequencies in phased arrays.

It is believed that the volcano smoke antenna (VSA) topology offers the unique advantages of simplicity, exceptional bandwidth (BW), and azimuthal omni-directionality over and against the other current approaches to broadband antennas. A recent work on the VSA [11] has made a case for further investigation of this structure. An omni-directional antenna with a 5:1 BW was constructed and described as a simplified form of the VSA. The device described in that work had a well-defined shape, while the shape of the conventional volcano smoke antenna is currently not so well defined. It is the purpose of this article to investigate and present the fundamental characteristics of the VSA, particularly regarding bandwidth.

The combination of low-VSWR and stable radiation patterns is difficult to achieve with current approaches for bandwidths greater than 5:1 or even 3:1.

II. DESIGN AND CONSTRUCTION

A. Design

The lack of rigorous analytical investigation, coupled with a pressing demand to develop a new and better technology, has forced much of the research in the area of ultra-wide band antennas to be done from a variation of parameters approach [3]. The basic design of many of these wide-band antennas is well understood; however, device optimization is carried out by trial-and-error computing. Several models whose difference lies in only one characteristic are simulated over the same frequency band. Comparing enough tests provides understanding how device performance is affected by any given design parameter.

In this article, our research team chose to pursue a more traditional route of design. Recognizing the fundamental definition of any antenna as an impedance transformer and the goal of any broadband tapered-slot antenna to gradually perform this transformation, the method of curvilinear squares was employed. Curvilinear squares is a graphical approach to solving Laplace’s equation [12]. The design was performed by hand and ultimately produced the topology seen in Fig. 2. It may perhaps be thought of as a marriage of cylindrical antennas and the annular slot antenna.

The curves generated graphically were sampled and curve-fit to the following equations over the range (0 < x < 12cm, 0 < y < 12cm):

\[
x = -4.45 \times 10^{-6} y^7 + 1.55 \times 10^{-3} y^6 - 0.0215 y^5 + 0.132 y^4 - 0.353 y^3 + 0.416 y^2 - 0.161 y + 0.435, \quad (1)
\]
Base:

\[ y = 1.52 \times 10^{-4} x^7 - 6.43 \times 10^{-3} x^6 + 0.111 x^5 - 1.011 x^4 + 5.196 x^3 - 15.08 x^2 + 23.55 x - 12.37. \]  

(2)

Fig. 3 displays the curves from Eqs. (1) and (2) (dashed) against the original graphically sampled curves (solid).

The motivation for investigating the VSA was to develop, in conjunction with Rockwell Collins, an omni-directional device which would operate with a VSWR below 3:1 from 800 MHz up to 3 GHz. No specific design equations/parameters were available for the VSA, but the assumption was made, based on Fig. 15.1 of ref. [13, p. 692, 694], that the height of the VSA bulb should be approximately \( \lambda/4 \) (of the longest wavelength) above the highest point on the base. Thus, the constructed prototypes were 10cm tall and 20cm in diameter.

B. Construction

Two approaches were taken for reducing the designed VSA to practice. The first technique consisted of utilizing a rapid prototyping machine from the Mechanical Engineering department at Michigan Tech University (MTU). A wax model was produced by the machine and then coated in silver conductive paint (following in the steps of Kraus’ original work on the VSA in the 1940s). The second prototype was turned on a lathe from a block of aluminum.

Each approach had significant strengths and weaknesses. The wax model offered a higher level of accuracy to the design parameters, but seemed to have a higher VSWR across the band. The aluminum model offered a significantly improved VSWR, but was not as close to the design curves as the wax model because the lathe was hand-operated and the curve was visually estimated by a machinist. Additionally, because the bulb must be electrically isolated from the base yet still mechanically supported, the wax model had fewer structural concerns than the aluminum one because its bulb, quite simply, weighed less. Despite the higher precision with the wax model and fewer bulb support problems, it was decided that the aluminum prototype offered more advantages, electrically, and a majority of the tests were carried out on it.

1) Wax Prototype: It was difficult to provide a solid connection without RF current disruption, between the Type N connector and the silver painted wax bulb. This may have contributed to the increased VSWR of the structure.

The RF frequency resistivity of the silver paint is unknown, but is anticipated to be significant at the upper microwave frequencies at which the prototype was tested, which would deteriorate radiation efficiency.

Rapid prototyping could be used with traditional electro-forming techniques to construct a high conductivity bulb and base assemblies with high precision. Because gold is typically utilized in the electroforming process, extremely low RF resistive loss is possible. Sacrificial wax forms of the bulb and base would be etched away as the last step of the electroforming process. This is particularly suited to higher frequency ranges of operation where the bulb dimensions are on the order of ten centimeters or less. A robust connection between the bulb and RF connector shaft could be realized by a solder process technique.

Recent advances in composite dielectric materials also would allow plating of non-sacrificial bulb and base.

2) Turned Prototype: Although the aluminum prototype was hand-turned on a metal lathe (Fig. 4), it is possible to replicate the design curves more accurately through contemporary CNC machining practices.

3) Structural concerns: The structural concerns of the unsupported bulb assembly can be readily alleviated by using a closed cell, with low dielectric and low loss foam encased with an electrically thin cylindrical radome structure.

III. Testing

A. MTU

The aluminum prototype was tested both at Michigan Tech University (MTU) and Rockwell-Collins, Inc. (RCI). The HP8752C network analyzer was used in conjunction with a log-periodic dipole test antenna to take radiation pattern measurements. VSWR was also recorded. Data was taken from 3 kHz to 3 GHz—the network analyzer’s limits—and all antenna directivity patterns (ADP) were normalized to 0 dB.
Fig. 4. Photograph of the aluminum VSA.

B. RCI

The Rockwell Collins measurements were performed with an Agilent 8510C network analyzer driven by an Orbit/FR 959+ automated antenna measurement system. The RCI anechoic chamber as measured reflectivity levels of less than -42 dB at 1 GHz and less than -65 for X Band frequencies. Co-polarized and cross-polarized absolute gain patterns (dBi) from 800 MHz - 15 GHz were measured. All patterns are referenced in decibels above isotropic (dBi), using the gain substitution method with appropriate standard gain antennas across the measured frequency band [14, pp. 94-96]. A close-up of the VSA prototype in the RCI anechoic chamber as it was for the VSWR measurements is shown in Fig. 4. Similarly, calibrated VSWR (S11) measurements were recorded with the Agilent 8510C from 800 MHz to 18 GHz. The VSA antenna was radiating within the anechoic chamber for these measurements.

IV. MODELING

Ansoft HFSS was used to build a computational model of the designed VSA. The initial model was simplified, only taking the curves into account; i.e., the feeding structure was ignored. This was done to obtain a better general understanding of basic device operation. A second model was generated to include the Teflon collar used for support in testing and the Teflon in the type-N connector. This alternative approach helped us gain a better grasp on what effect the Teflon is having on the device VSWR. Points were sampled from the curvilinear squares solution and the curves for the bulb and base were reconstructed graphically using a poly-line technique. The simulations were run on a PC with 1 GB of RAM and a 1 GHz processor. Although simulations were quite memory intensive (often requiring 2 GB or more, including swap), these results (see section V-B) represent an important step towards a more complete understanding of the VSA.

V. RESULTS

A. Experimental

The RCI measured co-polarized elevation ($\theta$) cuts are shown in Figs. 5 and 6 from 800MHz to 15GHz. The standard IEEE spherical coordinate system is used [14, p. 16]. The bulb axis of the VSA corresponds to the Z-axis (zenith) of the RCI anechoic chamber’s coordinate system. The radiation patterns were only recorded from the zenith to the horizon ($0 \leq \theta \leq 90^\circ$). This is due to the range tower absorber foam masking of the roll-over-azimuth range tower. A second set of measurements with the antenna mount reversed would be required to measure elevation ($\theta$) angles greater than 90°.

The measured radiation patterns exhibit several striking features. The VSA antenna operates very similar to an extremely broadband monopole antenna on a finite circular ground plane. At lower frequencies the “half donut” pattern of a monopole on an infinite ground plane is seen, and as the frequency is increased, pattern variations, characteristic of monopoles on finite ground planes, is readily apparent [15, 16]. The sharp zenith null characteristic of a monopole is retained throughout the frequency band.

1) VSWR: The simulated and measured VSWR of the VSA prototype is illustrated in Fig. 7. The plot shows the general trend of an extremely broadband radiating element, but with a higher overall VSWR than expected with several parasitic resonances.

2) Impedance Mismatch and the Type N connector/VSA bulb interface.: The curvilinear squares design procedure was first-order and did not account for the Teflon dielectric loading of the type N connector and the VSA’s input. The outer diameter of the VSA’s air filled throat diameter is...
coincident with the outer diameter dielectrically loaded of the type N connector. This represents an impedance mismatch between two coaxial transition lines, along with a capacitive discontinuity network. The characteristic impedance mismatch ($Z_0$) affects all frequencies of operations while the capacitive discontinuity network affects primarily the higher frequency bands.

3) Low Frequency Cut off: The VSA antenna exhibits a “lower frequency cut off” phenomenon. This supports previous research that suggests the VSA operates most efficiently when the antenna is approximately one-quarter wave long at the lowest operating frequency [13]. The VSA prototype studied was designed for a lower operating frequency of 800 MHz. The experimental curve of Fig. 7 exhibits a slight resonance with a VSWR of approximately 3.5:1 at this frequency.

At lower frequencies, the VSWR of the VSA sharply increases similar to that of an electrically small monopole on an infinite ground plane. The radiation resistance of the electrically small monopole (which is half that of an electrically small dipole due to image theory) is given by Eqs. 4-70 and 4-79 in ref. [16].

The choice of a type N connector limits the upper operational frequency to approximately 18 GHz, according to connector manufacturer specifications. Using the appropriate higher frequency connector will ensure maximum bandwidth.

Although the Volcano Smoke’s ultimate band width has not yet been precisely characterized, it is anticipated that the higher order wave guide moding at the coaxial feed/free space transition may dictate its upper frequency of operation. Moding may account for the general ringing of the VSWR as a function of frequency, although a more careful study of this question is necessary in order to make a conclusive statement. The next anticipated mode is the $TE_{11}$ cylindrical waveguide mode [17, p.447].

B. Simulation

1) VSWR: When determining operating bandwidths for wide-band antennas, a general rule of thumb used is a VSWR of 3:1 or better [18]. Simulation results in Fig. 8 demonstrate that the VSA has a minimum bandwidth of 10:1 (i.e. from

![Fig. 6. Comparison of simulated (on the left) and experimental (on the right) radiation patterns at 10GHz and 15GHz. The scales are in dB. The illustration at the bottom indicates the actual orientation of the graphs relative to the VSA.](image)

![Fig. 7. Simulated VSA VSWR, including the Teflon collar (one mode) and experimental VSA VSWR.](image)

![Fig. 8. Simulated VSA VSWR (one mode).](image)
smoke antenna is a potentially very wide-band device. Experimental data, supporting the original idea that the volcano
the device’s design parameters. Details of particular interest
for improving the current design are:

2) Radiation Patterns: The vertical radiation patterns in
Figs. 5 and 6 show that at higher frequencies the finite
ground plane can be seen to effect similar changes upon the
basic radiation pattern as is evidenced in a typical monopole
over a finite ground plane. As frequency increases, very few
significant lobes appear (with the exception, perhaps of the 10
GHz pattern), and majority of the pattern remains above the
horizontal. The azimuthal radiation patterns simply demon-
strated the omni-directionality due to device symmetry and
are not included. Cross-polarization patterns were typically
-20dB below the vertical-plane patterns and therefore also not
included here.

VI. CONCLUSIONS AND FUTURE WORK
We have demonstrated that the volcano smoke antenna
described has conservatively a 10 to 1 bandwidth for both
VSWR and antenna far-field pattern. Simulations over the
same frequency range show excellent agreement with the
experimental data, supporting the original idea that the volcano
smoke antenna is a potentially very wide-band device.
Future goals include developing a greater understanding of
the device’s design parameters. Details of particular interest
for improving the current design are:

1) Redesign the feed to have a broad band transition from
the coaxial connector
2) Use a higher frequency coaxial connector such as SMA
or SMB, etc.
3) Perform multi-mode FEM analysis of the structure to
find cut off of the 1st non-TEM mode
4) Parametric parameter study/optimization of bulb and
base shape function for a prescribed radiation pattern
and maximum band width
5) Foam load the antenna in a radome structure
   a) Alignment fixture to ensure radial mechanical
   symmetry for maximum broad band operation
   b) Robust mechanical design, i.e. shock and vibration
   c) Environmental robustness

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REFERENCES
[1] E. C. Jordan, G. A. Deschamps, J. D. Dyson, and R. E. Mayes,
"Developments in broadband antennas," IEEE Spectrum, pp. 59–71,
1964.
[3] K. Nagasawa and I. Matusuka, “Radiation field consideration of biconi-
[7] P. J. Gibson, "The vivaldi aerial," in 9th European Microwave Confer-
[8] E. Gazit, “Improved design of the vivaldi antenna,” in IEEE Proceed-
antenna for wide bandwidth phased arrays,” in IEE Proc. - Microwave
for ultra-wideband wireless systems,” in Proceedings of IEEE RAWCON
The Institute of Electrical and Electronics Engineers, Inc., New York,
Elements on Circular Ground Planes. Canton, MA: Artech House,
1987.

Lee Paulsen

Lee Paulsen was born in Ludington, MI on October 4, 1979. He received the B.S.E.E. degree from Michigan Technological University in 2001. Currently he is pursuing a Ph.D. degree at Michigan Technological University. His research interests include computational electromagnetics and numerical optimization of unique antenna topologies.

James B. West

Mr. James B. West is Engineering Manager / Senior Technol-
ogist, at Rockwell-Collins, Inc., Advanced Technology Center, Antennas and
Advanced Packaging Section He holds a B.S. (Electrical Engineering) from
Michigan Technological University, 1980, and a M.S. (Electrical Engineering),
Iowa State University, 1985. Mr. West has been with Advanced Technology
Center of Rockwell Collins, Inc. for 22 years and he is currently manager
of the Antennas and Advanced Packaging Technologies Section. He leads
the section in the areas of antenna and phased array antenna design and
metrology, electromagnetic computer simulation, RF applications of MEMs
and MicroMachining technology, passive microwave device design, and
semiconductor package design, simulation, and test. His project experience
includes weather radar; radar altimeter; mobile satellite communication;
INMARSAT-C SATCOM; hand held, airborne, munitions, and land mobile
GPS; Traffic Collision Avoidance System (TCAS); cellular radio systems;
Direct Broadcast System (DBS); Global Broadcast System (GBS); Direct
PC; aircraft GateLink; In-flight entertainment; Wireless Integrated Network
Sensors (WINS); SCAMP Milstar wide-band and FAB-T data links; and
Future Combat Systems High Band phased array development He is a member
of the IEEE Antennas and Propagation and Microwave Theory and Techniques
Societies, the Antenna Measurement Techniques Association (AMTA),
and the Applied Computational Electromagnetics Society (ACES). Mr. West has
written 5 publications, has been awarded eleven patents, and has five patents
pending in the areas of antenna, phased array, and miniature RF filter
technologies.
W. F. Perger  Warren Perger is an Associate Professor at Michigan Tech University, with a joint appointment in the Physics and Electrical Engineering Departments. His active areas of research include the interaction of electromagnetic fields with materials and antennas-related problems.