Design of a new multi pattern ribbon microphone using lossy transmission line impedance analogy

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An improved multi pattern ribbon microphone has been designed using SPICE circuit analysis with an impedance analogy using the lossy transmission line element to simulate diffraction and time delays in a novel way. The resulting microphone has switchable figure 8, hypercardioid, an omnidirectional patterns with high bandwidth and sensitivity.

0. INTRODUCTION

Impedance analogies have long been used to simulate systems due to the equivalence between electrical elements and mechanical and acoustic elements. The SPICE transmission line element, while designed for electrical transmission, can be supplied with parameters that make the phase velocity the speed of sound rather than a fraction of the speed of light. These parameters are too large to be physically realized, but SPICE will happily run them. It is the purpose of this paper to show that using these as well as other electrical elements can give great insight in microphone design.

1. A REVIEW OF ACOUSTIC IMPEDANCE ANALOGIES

In an acoustic impedance analogy the flow variable volume velocity is represented by current and the across variable pressure is represented by voltage. This satisfies continuity requirements. Acoustics elements are as follows:

Inertance

This is the acoustic equivalent of mass, and is represented in the electrical circuit by an inductor.

For a short tube (neglecting end effects) the value of inductance L is:

$$\rho \frac{l}{a}$$

where rho is air density, l is tube length and a is tube cross sectional area.

This represents the air in the short tube.

Compliance

This is the acoustic springiness of air inside a closed container, perhaps open at one end. This is represented by a capacitor of value

$$\frac{V}{\rho c^2}$$

where V is the volume of the container, rho is air density, and c is the speed of sound.
It should be noted that one terminal of the capacitor must be grounded (atmospheric pressure) unless it is a diaphragm.

Viscosity/acoustic resistance

This element represents energy loss in the sound wave and is represented with a resistor.

Sound pressure source

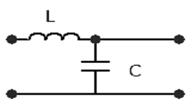
This is represented by an ideal voltage source.

Volume velocity source

This is represented by an ideal current source.

2. THE IDEAL TRANSMISSION LINE ELEMENT

First we'll consider a lossless Line.
In order to have a useful element we need the phase velocity to be the speed of sound, aproximately 343 m/s. In addition its characteristic impedance (for an infinite line) needs to be rho *c/a where rho is air density, c is the speed of sound, and a is line cross sectional area.
This makes a system of two equations with series inductance per unit length and shunt capacitance per unit length as shown in this incremental section:



For a transmission line phase velocity Vp is

$$\frac{1}{\sqrt{LC}}$$

and characteristic impedance is

$$Zo = \sqrt{\frac{L}{C}} \; .$$

We can simply divide Zo by Vp such that

$$\frac{\sqrt{\frac{L}{C}}}{\frac{1}{\sqrt{LC}}} = \frac{Zo}{343} \quad =L$$

So L=selected Zo/343

To find the capacitance/length for the line we can substitute L back in the formula

$$Zo = \sqrt{\frac{L}{C}}$$

solving for C

$$C = \frac{L}{Zo^2}$$

So these values will satisfy the area derived impedance and the speed of sound phase velocity.

Example
What transmission line parameters represent a .006 m diameter tube?

Zo is rho*c/area= 420/(Pi*.003^2)=14.85 megohm

L=Zo/343= 43307 H
C= L/Zo^2= 196pF

Checking Vp=1/sqrt(L*C)
= 1/sqrt(43307*196E-12)=343

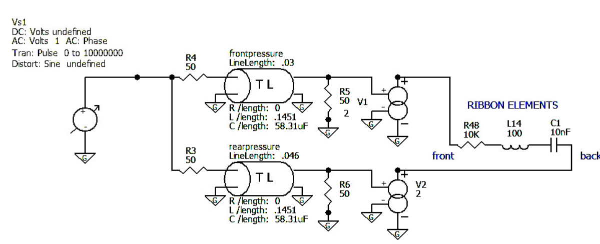
The inductance/length is unrealizably huge at 43307 Henries, but the SPICE transmission line model will run it with no issues.

3. USES FOR TRANSMISSION LINES IN MICROPHONE MODELS

Diaphragm front and back pressures

Pressure gradient microphone models need more than one sound port. An example is a figure 8 ribbon.
The path length from front to back can be modeled by two transmission lines terminated by their characteristic impedance driving voltage controlled voltage sources. This can be modified by radiation impedance elements and connect to the front and back of the diaphragm.diaphragm.

One of the sources can be varied to model off axis response, thus polar patterns can be generated.
Here is an example:



Note the two lines are terminated with their characteristic impedance, in this case 50 ohms.

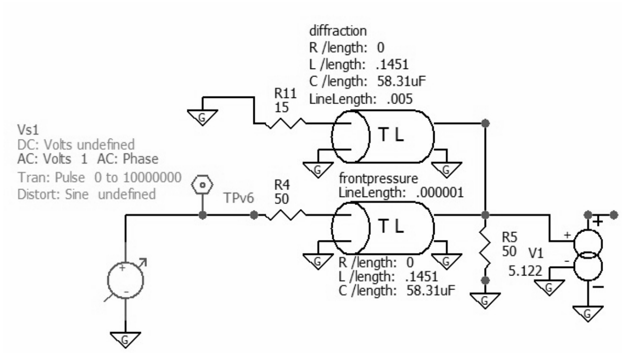
The top line is set to a length of 0.03m and the back line is set to 0.046m for a path length front to back of 0.016m or 16 mm. If the transmission lines are equal length 90 degrees off axis is represented, and if the rearpresssure line is shorter than the frontpressure line 180 degrees off axis can be represented. The ribbon elements represent inertance, compliance, and acoustic resistance with an inductor, capacitor, and a resistor respectively.

Diffraction effects

Transmission lines can also simulate pressure rise on diaphragms due to edge diffraction. For a circular diaphragm this typically results in a 10 dB peak in the center. Rectangular diaphragm structures have a similar peak.

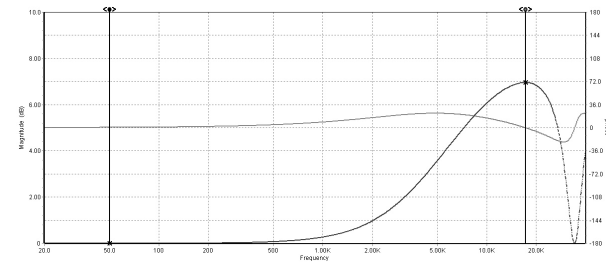
The way this is done is to send part of the signal to a mismatched transmission line. The mismatch will cause a reflection similar to that from an edge. If the correct mismatch is applied this will simulate the amplitude and phase due to diffraction.

Note the top stub transmission line added to the output of the forwardpressure line. It has a characteristic impedance of 50 ohms, but is terminated in a mismatched 15 ohm resistor that causes a reflection similar to the edge of a circular disk. The stub length is set to the disk radius of 5mm.



The voltage controlled voltage source gain is increased to compensate for loading effects of the stub impedance.

This results in the following correct pressure increase in magnitude and phase due to diffraction:



In this case the peak pressure is set to 7dB rather than the 10 dB rise seen at the center of the disk because not all diaphragm parts are at the center.

This applies fairly well to a rectangular shape like a ribbon magnet structure.

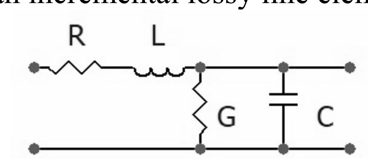
This applies to on axis radiation...off axis can be handled with different stub parameters.

4. LOSSY TRANSMISSION LINES

Many microphones have components that can be modelled by lossy lines. Examples are small diameter tubes and the felt stuffed labyrinth termination in the RCA ribbon microphones.

Lossless infinite lines have a real characteristic impedance, but in general lossy lines have a complex characteristic impedance.

Consider an incremental lossy line element:



Acoustically R can represent acoustic resistance, L an inertance, C a compliance, and conductance G a leak in the tube walls. We will consider solid walls, so G is set to zero (infinite resistance)

The characteristic impedance of the lossy line is:

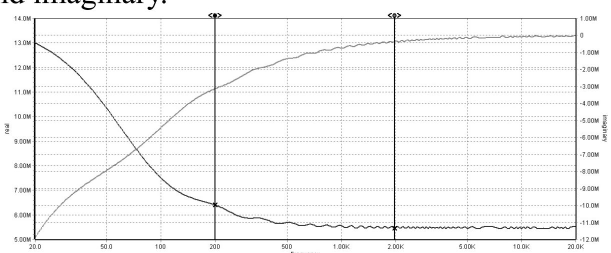
$$\sqrt{\frac{R+j\omega L}{G+j\omega c}}$$

which will generally be complex with non zero R and G.

We applied this in particular to the acoustic labyrinth used in cardioid and omni ribbon microphones for resistive loading. Typically

this is a folded tube about 8 mm diameter and up to 1 m long, terminated in a chamber. The folds and mismatched termination cause reflections, so tufts of felt are stuffed along the length of the tube to supress them.
We ran the spice model of an 8mm diameter pipe 1m long with 30 megohms/m series resistance, which corresponds to a very light fiber stuffing. The termination was a 36cm cubed chamber volume.
Calculated characteristic impedance for the unstuffed line was 5.48 megohm.

Here are the results of the run. This is a plot of the input impedance in rectangular form ; real and imaginary.



Above about 2 kHz the impedance is real (resistive) and the same as an unstuffed pipe.
However at LF resistance dramatically rises and the imaginary part goes strongly capacitive. This happens regardless of length past a certain point.

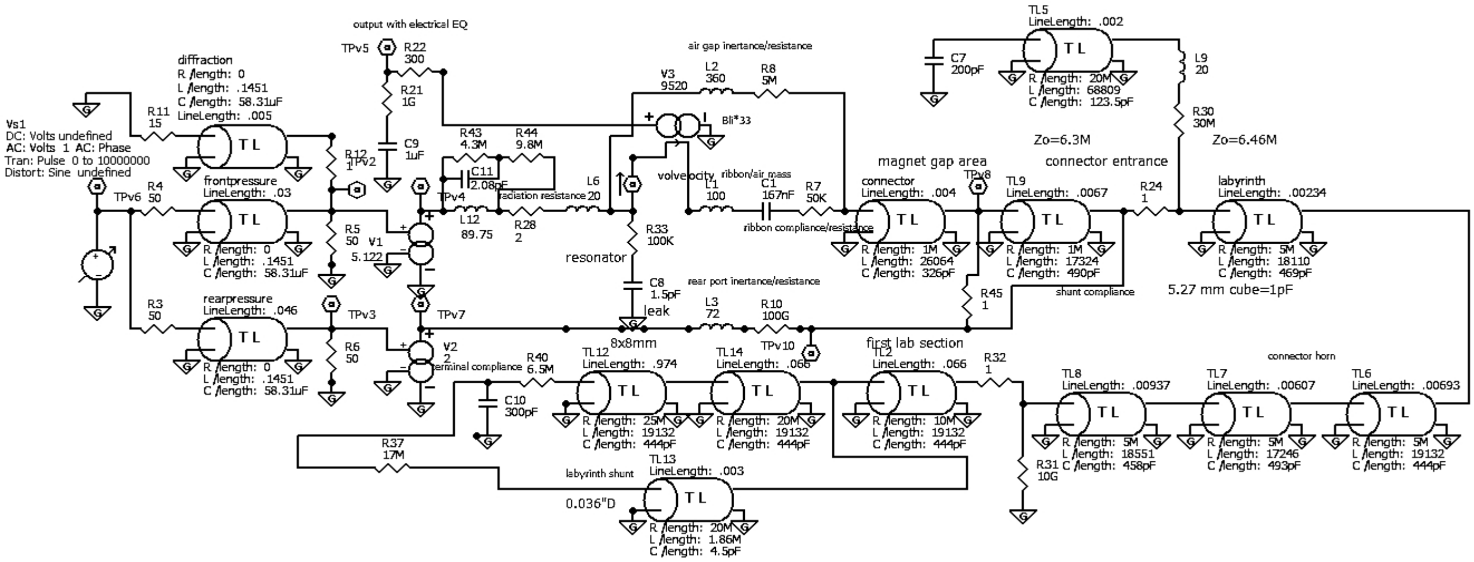
It was observed that many microphones that use a labyrinth to resistively load the diaphragm had poor bass response, including ours. This explains why. At LF the labyrinth looks like a small highly damped chamber rather than a constant resistance. The solution was to branch off to another network below 500 Hz.

5. THE MICROPHONE DESIGN

Given the insights gained from lossy transmission line SPICE analogies we set out to design a much improved multi-pattern ribbon.
We started with analysis of earlier multi -pattern microphones like the RCA 77DX. These microphones used a single ribbon, a folded stuffed labyrinth, and an inertance resistance low pass filter for a rear delay chamber. The inertance (a slot) could be varied in area by a rotating shutter to effect different patterns from figure eight and cardioid to omnidirectional.
The bandwidth was effectively a little over 10 kHz depending on the pattern selected. There was a large peak at 5kHz in the omni position.

Our first task was to find the source of the 5kHz peak. Simple SPICE models suggested that it was due to a reflection from the connector that couples the ribbon at right angles to the labyrinth. We found that to be the case...there was a large change in duct size causing reflections. At first we tried to tune it out with side stubs and resonant absorbers with mixed success. We found the best way was to make this connector a carefully shaped 90 degree horn.
We found the figure 8 performance of the 77DX somewhat wanting by modern standards. Analysis showed the connector as the cause again. It added to the front to back path even when the inertance aperture was fully open for figure 8.
We figured the best way to improve this was to use two ribbons...one unencumbered optimized for figure 8 with a second ribbon below it resistance loaded by a labyrinth for omni and cardioid use.

We would use Neodymium magnets in the structure rather than alnico, and do a finite element analysis of the magnet structure. This could result in higher output, some of which could be traded off for better high frequency response.
We would use waveplates, resonators, and resonant absorbers as needed to refine response.
The following shows the working SPICE impedance analog for the hypercardioid/omni section:



The analogy begins at left with the dual transmission lines for front and back pressure. Above them is the stub line to simulate diffraction. These drive voltage controlled voltage sources to make them zero impedance.

Next is a network that models the radiation impedance of the air load on the ribbon. At most frequencies this is almost purely inertive... the ribbon sees the air as a mass. This is followed by a resonator.

L1, C1, and R1 are the inertance, compliance, and resistance of the ribbon. Inertance in this case is the mass of the ribbon divided by area squared.

Shunting around the ribbon elements are L2 and R8 which represent the inertance and resistance of the air gaps between the ribbon and pole pieces. They are very high values if the gaps are small.

Current is measured in the ribbon leg. This represents volume velocity. Since the ribbon is fixed area this signal is proportional to electrical output. This model is acoustic only...for a complete electroacoustic model a transformer to convert to mechanical impedances and a gyrator element to convert to electrical output signals can be used. Then actual electrical output, loading effects, etc. can be simulated. The magnet gap area and the beginning of the labyrinth connector are then modeled by transmission lines. The rest of the connector is a stepped horn consisting of several short transmission line segments with gradual change in area.

Also at the beginning of the connector is a branch going back to the rearpressure source through L3 and R10. This is the inertance used in the delay chamber. It's about a 3mm diameter hole to the outside. You can see in this model there are actually two holes 6mm apart. As shown R10 is set to 100G indicating the holes are closed.

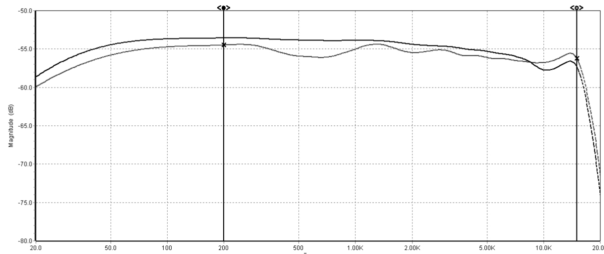
TL12, TL14, and TL2 form the labyrinth proper. The actual labyrinth consists of a bundle of 15 connected sections. Total length is 1.1 meter. These are terminated through a 6.5 Mohm screen to C10, the bottom cavity. It's about 30 cm cubed volume.

Between the first and second labyrinth sections a very short shunt to the cavity TL13 is connected via a 17Mohm screen. This is a modified Thuras tube that works with the cavity to bypass low frequencies below 500 Hz to solve the loss of bass from the labyrinth stuffing as previously mentioned. At higher frequencies its reactance effectively closes it. This increases low bass in the omni position by about 5 dB.

The tube is a 1mm diameter hole 3mm deep.

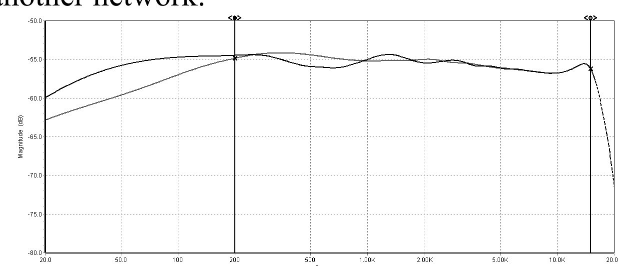
We will now look at some spice runs while varying parameters.

First we look at opening and closing the back vent hole.

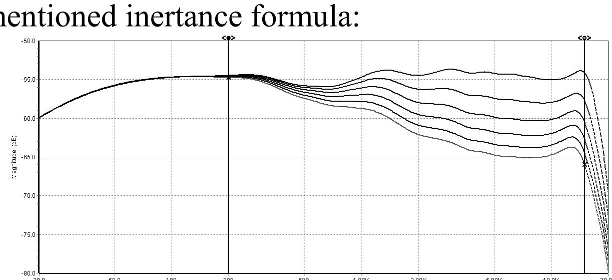


The lower line is with hole closed, and the microphone is omnidirectional. The upper line is hypercardioid.
The response is smooth, within about 3dB from 30 to 17kHz. In hole closed position there is a broad 2 dB dip at 500 Hz. This is caused by the Thuras tube branch causing an impedance bump in the labyrinth and a slight reflection.

Now with hole closed (omni position) we will open and close the Thuras tube.The small dip at 500 Hz is a small price to pay for the extra bass when the Thuras tube is open (upper line). It turns out the dip can be removed with another network.

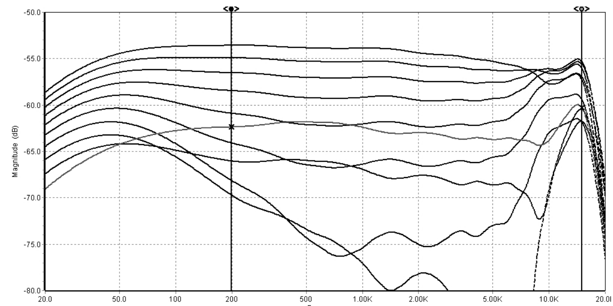


We will now change the ribbon thickness from 5 to 0.5 microns using the previously mentioned inertance formula:



It's obvious this type of resistance controlled omni ribbon microphone doesn't like heavy ribbons. The mass reactance catches up with things at HF. We selected 1.2 micron material.

Finally we'll explore off axis response by sweeping the delay in the rearpressure above and below the frontpressure delay. The back hole is open for this run.This shows roughly a hypercardioid pattern with a 10dB down back lobe.

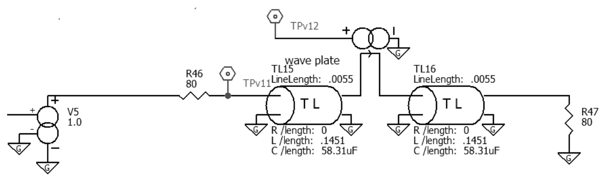


This also shows typical single D unidirectional response...deep cancellation occurs only at one frequency because the single pole LR delay network doesn't have constant group/phase delay and it shuts off at about 8 kHz turning the unit into a pressure microphone.

Since the on axis diffraction doesn't happen the same off axis we also swept the diffraction transmission line down in length as we went from front to back, but this is only a rough aproximation. Better to switch in different networks for other angles designed to model off axis diffraction properly.

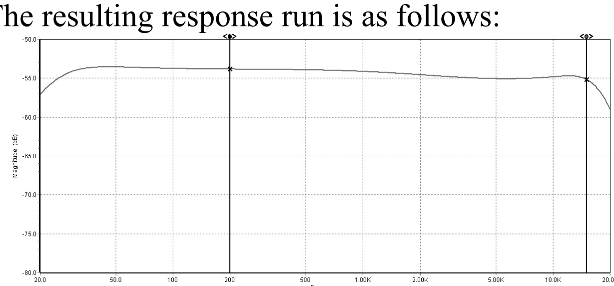
The upper figure 8 ribbon is almost trivial compared to the lower one. In the model we remove all the labyrinth hardware, add a radiation reactance to the back side, slightly reduce the path length with drilled holes in the magnet structure, and add wave plates. We also add damping screens to prevent resonant peaks at the ribbon resonance and harmonics.

Wave plates are perforated grilles mounted in front and in back of the ribbon. These cause a pressure gradient peak in between them and thus a response peak, much like a room resonance in a partly acoustically transparent walled enclosure. The location and amount of boost are controlled by the spacing and percent open of the grilles.
These can easily be modeled with SPICE transmission lines:



The output signal is sent to the voltage controlled voltage source which is then sent to two equal length 50 ohm transmission lines with mismatched 80 ohm terminations. The modified signal is taken as the current between the two lines. The values selected give about a 4dB peak at 14kHz.

The resulting response run is as follows:



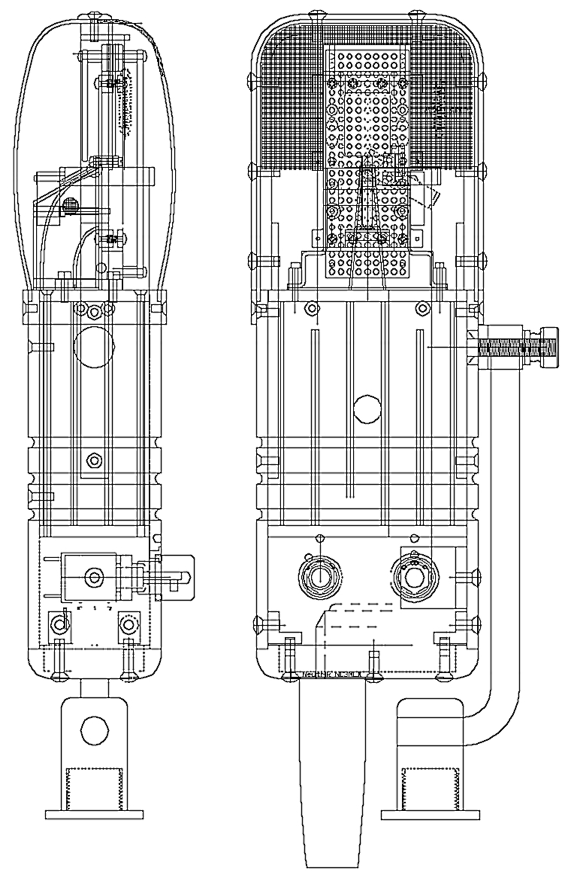
Response is almost perfectly flat from 30 to 15kHz, with 20 and 20kHz about 5 dB down. Response can be extended even further by reducing front to back path length, trading HF response for sensitivity. With neodymium magnets, wave plates, diffraction, and damping screens it's very easy to design a very high performance figure 8 ribbon with the help of the SPICE model to tweak components.

6.THE FINAL PRODUCT DESIGN

The resulting product designed by this method is known as the Polyribbon. It has three patterns selected by a front knob: omnidirectional, hypercardioid, and figure 8. The knob actuates a valve controlling the inertance port and also selects electrically between the two ribbons. The ribbon sizes are 2.5x18mm each. A 33% open wave plate is applied to the figure 8 ribbon and a front resonator is fitted to the bottom omni/hypercardioid ribbon. The figure 8 ribbon has damping screens applied front and back, and the resulting reduced bass response is compensated for by a frequency selective baffle. There is a three way bass cut switch for proximity effect using a pot core tapped inductor. Useful response extends to 18kHz in figure 8 mode and 25kHz in omni and hypercardioid. Output is very high at 2.5 mV/Pascal.

The goal was to produce a modern equivalent to microphones like the RCA 77 series with vastly improved performance. Transmission line SPICE models were instrumental in achieving this goal. At this time of writing it is the only known multipattern ribbon microphone being manufactured. We think Dr. Harry Olson and Oliver Heaviside would be pleased.

This is a cutaway drawing showing construction:



Leslie Watts served as a development engineer at Shure Brothers incorprated. Later he took positions as Director of Research and Development at ITW Chronomatic division then Corporate Engineer at ITW corporate headquarters. He then started L M Watts Technology, designing acoustic and other components for ITW, Electrovoice, and others. He has numerous patents in the fields of optics, electroacoustics, consumer products, and automotive.

Leslie graduated from the Herbert W. Wertheim school of engineering at the University of Florida with a BSE in aerospace engineering science. He currently spends the winter months on a sailboat in the tropics.