IMPEDANCE MATCHING FOR LONG CABLES CARRYING ULTRASONIC SIGNALS. (U)

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IMPEDANCE MATCHING FOR LONG CABLES CARRYING ULTRASONIC SIGNALS

JOHN MITTLEMAN

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### Impedance Matching for Long Cables Carrying Ultrasonic Signals

**Title:** Impedance Matching for Long Cables Carrying Ultrasonic Signals

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**Abstract:**
Long coaxial cables, when used for ultrasonic inspection, have been known to produce extraneous signals and attenuate valid signals. In this report, the theory of transmission lines is applied to such cables and is shown to predict the unwanted phenomena. The theory is then applied to the design of matching networks composed of one resistive and one inductive component. A series R-L network placed in parallel with the transducer is shown to produce a satisfactory impedance match, and its performance is demonstrated through...
20. ABSTRACT (continued):

experiments on a 1000-foot length of coaxial cable terminated by the network and an ultrasonic transducer.
LIST OF SYMBOLS

A  Attenuation constant for a known cable length (dB)
B  Phase constant for a known cable length (degrees)
C  Capacitance (Farads)
E  Voltage (volts)
E_L  Voltage at the load (receiving) end
E_S  Voltage at the generator (sending) end
F  Frequency (Megahertz)
I  Current (Amperes)
I_L  Current at the load end
I_S  Current at the sending end
L  Inductance (Henries)
R  Resistance (ohms)
Z  Impedance (complex), (ohms)
Z_o  Characteristic impedance
Z_g  Source (generator) output impedance
Z_L  Load input impedance
Z_s  Cable input impedance at the sending end
Z_s (short)  Z_s with the load end short circuited
Z_s (open)  Z_s with the load end open circuited
Z_sc  Z_s (short)

c  Speed of light in a vacuum (~ 3 x 10^8 m/sec)
e  Base of natural logarithms (2.718...)
j  \(\sqrt{-1}\)
\(\ell\)  Cable length (feet or metres)
\[ v \]  
Speed of electromagnetic wave propagation in a material

\[ a \]  
Attenuation constant \( \frac{\text{dB}}{1000 \text{ feet}} \) or \( \text{nepers} \)

\[ \beta \]  
Phase constant \( \frac{\text{degrees}}{1000 \text{ feet}} \) or \( \frac{\text{radians}}{\text{metre}} \)

\[ \gamma \]  
Propagation constant \( (a + j\beta) \)

\[ \pi \]  
Pi (3.141...)

\[ \tau \]  
Time (seconds)

\[ \omega \]  
Angular frequency \( \frac{\text{radians}}{\text{second}} \)
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BACKGROUND

Underwater ultrasonic testing at the Naval Coastal Systems Center (NCSC) is performed by a team composed of a diver and a topside technician. Sufficient transducer cable is used so that all test hardware remains out of water, except the transducer.

Unfortunately, the long transducer cable acts as an electrical network for which neither the ultrasonic pulser/receiver nor the transducer was designed, so the quality of ultrasonic signals is often degraded. At first, it was thought that amplification of the signals generated by the transducer would restore the signal quality; but it was later realized that the fundamental problem is created by impedance mismatches which foster reflections and decrease power transmitted to and from the transducer.

During 1980 efforts to increase the usable transducer cable length centered around impedance matching network design.

BASIC EQUATIONS

In our impedance matching design work, the following basic equations which relate electrical conditions at the ends of a transmission cable were used:

\[ E_s = (E_L + I_L Z_o) \left( e^{\gamma l} \right) / 2 + (E_L - I_L Z_o) \left( e^{-\gamma l} \right) / 2 \]

and

\[ I_s = (E_L + I_L Z_o) \left( e^{\gamma l} \right) / 2Z_o - (E_L - I_L Z_o) \left( e^{-\gamma l} \right) / 2Z_o \]

where \( E_s \) and \( I_s \) are voltage and current at the sending end

\( E_L \) and \( I_L \) are voltage and current at the receiving end

Z₀ is the cable's characteristic impedance

γ is a propagation constant and

l is the cable length

Note that for an infinitely long cable (in which there is no reflected wave) the term $e^{-\gamma l}$ drops out and the sending end impedance is the characteristic impedance, $Z₀$.

$$Z_s \ (for \ l = \infty) = \frac{E}{I_s} \ (for \ l = \infty) = Z₀ \ .$$

Also note that the equations are reminiscent of hyperbolic functions; in fact, for the load end open circuited or short circuited the input impedances are

$$Z_s \ (open \ circuit \ at \ load \ end) = Z₀ \ coth \ \gamma l$$

or

$$Z_s \ (short \ circuit \ at \ load \ end) = Z₀ \ tanh \ \gamma l \ .$$

For any other load impedance the input impedance can be expressed as

$$Z_s \ (for \ Z_L \ at \ load \ end) = Z_s \ (open) \ \frac{Z_s \ (short) + Z_L}{(Z_s \ (open) + Z_L)} \ .$$

Looking from the load end toward the pulser/receiver (which has an internal impedance of $Z₀$) the equations can be written in much the same fashion. This leads to the following configuration:
The possibilities for mismatched impedances are numerous. Inefficient power transfers and troublesome reflections can occur at both cable ends unless impedances are properly matched. This is not easy since the load impedance (the transducer's impedance) varies as a function of frequency. The term "matching" is somewhat deceiving in that it does not mean equating the impedances looking up and down the cable from any given point. Rather, it means making the impedance looking either direction from any point on the cable equal to the cable's characteristic impedance. Though this is a more restrictive requirement than having equal impedances looking in both directions, it is not as bad as first thought because if both ends are terminated in a device having an input impedance equal to the characteristic impedance ($Z_g = Z_L = Z_o$) then the input impedance of the terminated cable becomes:

$$Z_s = Z_o \coth \gamma L \left[ \frac{Z_o \tanh \gamma L + Z_o}{Z_o \coth \gamma L + Z_o} \right] = Z_o$$

showing that cable length and the propagation constant drop out of the expression.

To predict performance if $Z_L$ or $Z_g$ is not equal to $Z_o$ the variables seen in the preceding expressions; namely, $Z_o$, $\gamma L$, $Z_g$, and $Z_L$ must be quantified. The following discussions pertain to this quantification.

CABLE PARAMETERS

Cable parameters are, at best, difficult to measure, and manufacturer's information is often available at only a few selected frequencies. However, with modern electronic impedance measuring instruments the task is tractable.

Let us consider what measurements would be of use. Knowing that $Z_{sc} = Z_o \tanh \gamma L$ (where $Z_{sc}$ indicates the cable's input impedance with the load end short circuited) allows calculation of the magnitude (or phase) of the cable's input impedance when the cable is short circuited if $Z_o$ (the characteristic impedance), $\gamma$ (the propagation constant), and $L$ (the cable length) are known. Alternatively, measurements can be taken and calculations made to determine the unknown constants. For instance, if the magnitude of $Z_{sc}$ (denoted $||Z_{sc}||$) and the angle of $Z_{sc}$ (denoted $\angle Z_{sc}$) are measured then $\gamma L$ and $Z_o$ can be determined as follows:
\[ Z_{sc} = Z_0 \tanh \gamma z \]

\[ \|Z_{sc}\| = \|Z_0\| \|\tanh \gamma z\| \]

and

\[ x Z_{sc} = x Z_0 + x \tanh \gamma z \]

Since \( \gamma z \) may be complex, let us substitute \( A + jB \) for \( \gamma z \).

Then

\[ \|Z_{sc}\| = \|Z_0\| \|\tanh (A + jB)\| \]

By straightforward algebraic manipulation we find

\[ \tanh (A+jB) = \frac{e^{A+jB} - e^{-(A+jB)}}{e^{A+jB} + e^{-(A+jB)}} \]

reduces to

\[ \tanh (A+jB) = \frac{e^{2A} - e^{-2A} + 2j \sin 2B}{e^{2A} + e^{-2A} + 2 \cos 2B} \]

from which

\[ \|\tanh (A+jB)\| = \frac{(e^{4A} + e^{-4A} - 2 \cos 4B)^{1/2}}{(e^{2A} + e^{-2A} + 2 \cos 2B)} \]

Note that \( A = \alpha z \) (the attenuation constant) and \( B = \beta z \) (the phase constant) can be expected to be smoothly increasing functions of frequency. Thus, periodicity in \( \|\tanh \gamma z\| \), (or, since \( \|Z_0\| \) is also expected to be a slowly varying function of frequency, periodicity in \( \|Z_{sc}\| \)) is attributable to the periodic nature of \( \cos 2B \) and \( \cos 4B \), and will produce local extrema when \( 2B \) is approximately equal to a multiple of \( \pi \) (180°). When this is the case,

\[ \|Z_{sc}\| \approx \|Z_0\| \left(\frac{e^{4A} + e^{-4A} + 2}{e^{2A} + e^{-2A} + 2}\right)^{1/2} \]

which reduces to

\[ \|Z_{sc}\| = \|Z_0\| \tanh A \text{ (at local minima)} \]
or

\[ \| Z_{sc} \| = \| Z_0 \| \coth A \text{ (at local maxima)} \]

With these two equations in hand we are ready to use measurements of \( Z_{sc} \) since we now know that (at least approximately)

a. The upper envelope of \( \| Z_{sc} \| \) is \( \| Z_0 \| \coth A \).
b. The lower envelope of \( \| Z_{sc} \| \) is \( \| Z_0 \| \tanh A \).
c. Local maxima of \( \| Z_{sc} \| \) occur at \( B \) equal to odd multiples of \( \pi/2 \).
d. Local minima of \( \| Z_{sc} \| \) occur at \( B \) equal to even multiples of \( \pi/2 \).

For \( A \), \( B \), and \( Z_0 \) varying smoothly as functions of frequency, interpolation between extrema can be used to find

\[ \| Z_0 \| = (\| Z_{sc} \| \text{ upper envelope} \| Z_{sc} \| \text{ lower envelope})^{1/2} \]

and \( \tanh A = (\| Z_{sc} \| \text{ upper envelope} \| Z_{sc} \| \text{ lower envelope})^{1/2} \)

from which \( A \) can be calculated

\[ A = \frac{1}{2} \ln \left( \frac{1 + \tanh A}{1 - \tanh A} \right) \]

The extrema themselves are used to plot \( B \) as a function of frequency since extrema occur at \( B \approx n\pi/2 \).

This procedure was applied to measurements taken on 1000 feet of RG-58 coaxial cable. Impedance measurements were made every 0.02 MHz from 0.5 MHz to 6.48 MHz using the instrumentation shown schematically in Figure 1. These impedance values (Figure 2) were the basis for calculations leading to values of \( \| Z_0 \| \), \( A \), and \( B \) shown in Figures 3, 4, and 5. Curve fitting yielded the following expressions which, while approximate, serve well for calculations:

\[ Z_0 \approx 50\Omega \]

\[ A \approx (4.8 \sqrt{F} - 1.4) \text{ dB} \]

\[ B \approx 564F \text{ degrees} \]

where \( F \) is frequency, in megahertz.
FIGURE 1. INSTRUMENTATION FOR CABLE PARAMETER MEASUREMENTS
FIGURE 4. ATTENUATION COEFFICIENT

ATTENUATION COEFFICIENT (dB/1000ft)
NCSC TM 325-81

Figure 5: Phase Constant

Phase Constant (in increments of $\pi/2$)

Frequency (MHz)
And finally, the characteristic impedance $Z$ has a small imaginary (reactive) component, but it is typically ignored. Measurements of $Z_{sc}$ were taken, and from these $4Z_o$ was found to be only a few degrees.

LOAD PARAMETERS

The ultrasonic transducer (the load) is primarily a capacitive device. Off-the-shelf pulser/receivers (ultrasonic instruments) are typically designed to excite this sort of load quite effectively. However, when the transducer is at the end of a long cable, instead of looking into an impedance of $1/jωC$ (a capacitor) the pulser/receiver looks into an impedance of

$$Z_o \frac{\tanh γL + \frac{1}{jωC}}{Z_o \coth γL + \frac{1}{jωC}}$$

Figure 6 shows the capacitive characteristics of a transducer swamped by the presence of a long cable, and clearly indicates that remedial action is required. First, it would be desirable to terminate the cable in such a way as to prevent reflections from occurring since they show up at the receiver amplifier of the ultrasonic instrument and create problems. The following example shows one method of matching and its effect on input impedance.

First, the transducer’s input impedance is measured and modeled (Figure 7). In this case, a 1/2-inch unfocused transducer with a 2.25 MHz center frequency is modeled well by a 1.0 nanofarad capacitor. Then, to make the load impedance 50 ohms (pure real) at 2.25 MHz, a series resistor-inductor combination is placed in parallel with it.

The objective is to make the network’s input impedance, $Z$, equal to $Z_o$ at 2.25 MHz. Using the model shown below the input impedance and appropriate values of components are calculated:

$$Z = \frac{(R + jωL)(1/jωC)}{[R + jωL + (1/jωC)]}$$

$$Z = \frac{(R + jωL)[jωRC + (1 - ω^2LC)]}{1}$$
Separating this into a real and imaginary part gives

\[ Z = \frac{R}{(1-w^2LC)^2 + (wRC)^2} + \frac{L}{C} \frac{1 - w^2LC - R^2}{(1-w^2LC)^2 + (wRC)^2} \]

For \( Z \) to equal \( \mathcal{Z}_o + j0 \) (a pure real value),

\[ 0 = \frac{L}{C} (1-w^2LC) - R^2 \]

from which \( R = \frac{L}{C} (1-w^2LC)^{1/2} \).

Also, \( Z = \frac{R}{(1-w^2LC)^2 + (wRC)^2} \) must be made to equal \( \mathcal{Z}_o \).

Substituting the expression for \( R \) and solving gives

\[ L = \frac{\mathcal{Z}_o^2 C}{1 + \mathcal{Z}_o^2 w^2 C^2} \]

and \( R = \frac{\mathcal{Z}_o}{1 + \mathcal{Z}_o^2 w^2 C^2} \).

In the case we have chosen, where

\[ \mathcal{Z}_o = 50\Omega \]
\[ C = 1.0 \times 10^{-9} \text{ Farad} \]
\[ w = 2\pi \times 2.25 \times 10^6 \text{ Hz} \]

we find \( \mathcal{L} = 1.667 \times 10^{-6} \text{ Henry} \)
\( \mathcal{R} = 33.34\Omega \).

The impedance of this network as a function of frequency is shown in Figure 8, and its effect on the cable's input impedance is shown in Figure 9. Comparison of Figure 9 with the unmatched case (Figure 6) shows that a substantial improvement has been made.

The series R-L network in parallel with the transducer is not the only available configuration. In fact, limiting the choice to one resistor and one inductor allows three additional configurations:
INPUT IMPEDANCE OF THE TRANSDUCER
MATCHED BY A SERIES R-L NETWORK
IN PARALLEL WITH IT

\[ C \text{(transducer)} = 1.8 \text{ nanofarad} \]
\[ R = 33.3 \text{ ohms} \]
\[ L = 1.687 \text{ microhenry} \]

(MATCH AT 2.25 MEGAHertz)

**Figure 8. Matched Transducer Impedance**
INPUT IMPEDANCE OF 1000 FEET OF RG-59 COAXIAL CABLE TERMINATED BY A SERIES R-L NETWORK IN PARALLEL WITH THE TRANSDUCER.

\[ R = 33.34 \text{ OHMS} \]
\[ L = 1.667 \text{ MICROHENRY} \]
\[ C(\text{transducer}) = 1.0 \text{ NANOFARAD} \]

(IMPEDANCE MATCH AT 2.25 MHz)

FIGURE 9. CABLE AND SERIES MATCHED TRANSDUCER IMPEDANCE
Options (c) and (d) have the unfortunate characteristic of reducing the voltage applied to the transducer and are therefore eliminated from consideration. Option (b) was studied since it allows full voltage to be applied to the transducer. Shown in Figure 10 are measured data and the theoretical curve for this configuration. This figure shows that at frequencies below 2.25 MHz the performance of this configuration is not as good as the series R-L network in parallel with the transducer (option (a)).

Other configurations which might perhaps utilize a wide-band transformer in the matching network have not been studied.

IMPLEMENTATION

Having found that a series R-L network in parallel with the transducer improves the transmission of pulses to the transducer, the next objective was to implement this network in hardware. Several approaches are possible, and one of these is described below. Since mechanical strength, small size, and waterproofed construction are desirable qualities it was decided to wind the inductor around the coaxial cable and put the entire network in the standard NCSC cable termination which mates with the standard NCSC transducer housing. With no particular attempt to optimize the construction (by choosing a very fine wire size whose resistance and inductance would be correct without an additional resistor) a number 31 magnet wire was investigated and found to give approximately 1 microhenry per 20 turns around the coaxial cable (Figure 11). Thus, 33 turns in series with a 33 ohm resistor would form a suitable network. The steps used in building this are shown in Figure 12.
Comparison of theoretical and measured impedance values for 1000 feet of RG-58 coaxial cable terminated by an ultrasonic transducer and a parallel R-L network to match the transducer’s capacitance at 2.25 MHz.

Figure 10. Cable and parallel matched transducer impedance.
FIGURE 11. IMPEDANCE OF WIRE COILS

IMPEDANCE OF #31 MAGNET WIRE WRAPPED AROUND RG-58 COAXIAL CABLE

• 60 TURNS
x 40 TURNS
•• 20 TURNS

MAGNITUDE OF IMPEDANCE (OMS)

NCSC TM 325-81
(a) 33 turns of No. 31 magnet wire whipped around coaxial cable.

(b) 33Ω resistor soldered on and heat shrink tube applied around windings and resistor.

(c) Cable braid bared and resistor lead soldered to it. Heat shrink tubing then applied over braid and coil lead.

(d) BNC plug nut, washer, gasket and clamp applied in normal manner. Center conductor bared and soldered to coil lead.

(e) Center conductor pin soldered on and heat shrink tubing applied over dielectric and coil lead.

(f) BNC plug completed and assembly potted into cable terminal.

FIGURE 12. NETWORK CONSTRUCTION
The results of this construction applied to a 740-foot length of C-N-4 coaxial cable are shown in Figures 13a through 13d. It should be noted that C-N-4, like RG-58, has a characteristic impedance of 500. C-N-4 differs from RG-58 primarily in its jacket which is an abrasion resistant non-hosing (water blocking) neoprene rather than plastic material. Electrically, the two cables are quite similar. Figures 13a and 13c show conditions at the pulser and the transducer, respectively, for the cable before the matching network was connected. Evident in Figure 13a are a series of initial pulses rather than a single spike. The spacing between pulses indicates that 2.26 microseconds separate them. We calculate the time it would take an electromagnetic wavefront to travel 1480 feet of cable (round trip in a 740-foot length) as follows:

$$\tau = \frac{2d}{v} = \frac{2d}{\left(\frac{2}{3}c\right)}$$

Since the electromagnetic wave's propagation velocity in a cable filled with the dielectric used is about two-thirds the speed of light in a vacuum.

$$\tau \approx \frac{2 \times 740 \text{ feet}}{0.67 \times 3 \times 10^8 \text{ m/sec}} \times \frac{\text{metre}}{3.28 \text{ feet}} = 2.25 \text{ microseconds}$$

This agreement with the time interval read off the oscilloscope screen helps confirm that reflections can and do occur. Their detrimental effect on the received waveform is shown in Figure 13b in which both the received waveform (upper) and the video presentation (lower) are shown. The first three spikes, from left to right on the video portion are the front surface echo, a spurious spike resulting from the reflection, and the first backwall echo from a 0.75-inch thick aluminum specimen. An ultrasonic inspector using this unmatched cable would have no way of determining the false indication from an internal defect or a thin area. Figures 13c and 13d show what occurs when the matching network is connected. First, the initial pulse is considerably cleaner and second, since the transducer is excited only once, the false indication disappears from the video presentation.

CONCLUSIONS

With suitable matching networks "off-the-shelf" NDT ultrasonic testing instrumentation can be operated with long (1000-foot) pulse generator-to-transducer cabling. This permits the instrumentation to be located topside where a UT technician can analyze the data in relative comfort. Also, with computer assistance the UT technician can analyze large amounts of data, edit it, and have it in report format shortly after the test is completed.
FIGURE 13. WAVEFORM COMPARISONS

(a) Pulse Output, Unmatched
(b) Return Signals, Unmatched
(c) Pulse Output, Matched
(d) Return Signals, Matched
Formulae developed in this paper for impedance matching of cables and transducers will be useful in matching problems occurring in other systems. Of particular interest is that terminating a cable in its characteristic impedance eliminates the dependence of input impedance on cable length. Thus, the same network will work on both long and short cables. Although the transducer's impedance affects network design, most commonly used ultrasonic transducers have a capacitance near 1000 picofarads; thus, relatively few different network designs can accommodate most common transducers.

RECOMMENDATIONS

It is recommended that all cables used for underwater ultrasonic testing be impedance matched during construction of the waterproofed electrical termination.
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821 Commanding Officer, USS SIMON LAKE (AS 33), FPO Miami 34085
822 Commanding Officer, USS L. Y. SPEAR (AS 36), FPO New York 09547
823 Commanding Officer, USS DIXON (AS 37), FPO San Francisco 96648
824 Commanding Officer, USS PROTEUS (AS 19), FPO San Francisco 96646
825 Commanding Officer, USS SPERRY (AS 12), FPO San Francisco 96645
826 Commanding Officer, USS KITTIWAKE (ASR 13), FPO New York 09501
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830 Commanding Officer, USS FLORIKAN (ASR 9), FPO San Francisco 96601
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832 Commanding Officer, USS PAILUTE (ATF 159), FPO New York 09501
833 Commanding Officer, USS PAPAGO (ATF 160), FPO New York 09501
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835 Commanding Officer, USS MOCTOBI (ATF 105), FPO San Francisco 96601
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837 Commanding Officer, USS TAKELMA (ATF 113), FPO San Francisco 96601
838 Officer in Charge, YRST 2, Harbor Clearance Unit TWO, FPO New York 09501
839 Commanding Officer, USS EDENTON (ATS 1), FPO New York 09501
840 Commanding Officer, USS BEAUFORT (ATS 2), FPO San Francisco 96601
841 Commanding Officer, USS BRUNSWICK (ATS 3), FPO San Francisco 96601
842 Officer in Charge, Underwater Construction Team ONE, Naval Amphibious Base, Little Creek, Norfolk VA 23521
843 Officer in Charge, Underwater Construction Team TWO, Naval Construction Battalion Center, Port Hueneme, CA 93043
844 Director, Hawaii Laboratory, Naval Ocean Systems Center, Kaneohe, HI 96863
354 Commander, Annapolis Laboratory, David W. Taylor Naval Ship Research & Development Center, Annapolis, MD 21402
487 Commander, Annapolis Laboratory, David W. Taylor Research & Development Center, Bethesda, MD 20034
845 Officer in Charge, Fort Lauderdale Facility, Naval Surface Weapons Center, 1650 SW 39th St., Port Lauderdale, FL 33315
498 Commanding Officer, New London Laboratory, Naval Underwater Systems Center, New London, CT 06320
846 Officer in Charge, Newport Laboratory, Naval Underwater Systems Center, Newport, RI 02840
847 Officer in Charge, Civil Engineering Laboratory, Naval Construction Battalion Center, Port Hueneme, CA 93043
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862 Officer in Charge, Engineering Duty Officer School, Mare Island, Vallejo, CA 94592
863 Commanding Officer, Naval School, Explosive Ordnance Disposal, Naval Ordnance Station, Indian Head, MD 20640
864 Commanding Officer, RHCU DET 522, Naval Reserve Center, 860 Terry Ave., N., Seattle, WA 98109
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868 Commanding Officer, RHCU DET 304, Naval Reserve Center, Bldg. 662, Naval Base, Philadelphia, PA 19112
869 Commanding Officer, RHCU DET 405, Naval Reserve Center, 1089 E. 9th St., Cleveland, OH 44114
870 Commanding Officer, RHCU DET 506, Naval & Marine Corps Reserve Center, Naval Amphibious Base, Little Creek, Norfolk, VA 23520
871 Commanding Officer, RHCU DET 608, Naval & Marine Corps Reserve Center, Naval Amphibious Base, Little Creek, Norfolk, VA 23520
872 Commanding Officer, RHCU DET 608, Naval & Marine Corps Reserve Center, Box 44, Bldg 411, Naval Air Station, Jacksonville, FL 32212
873 Commanding Officer, RHCU DET 708, Naval Reserve Center, 2610 Tigertail Avenue, Miami, FL 33133
874 Commanding Officer, RHCU DET 813, Naval Reserve Center, Randolph St at Lake Michigan, Chicago, IL 60601
875 Commanding Officer, RHCU DET 110, Naval Reserve Center, Bldg 84, NAS, Corpus Christi, TX 78419
876 Commanding Officer, RHCU DET 220, Naval & Marine Corps Reserve Center, Bldg 2, Treasure Island, San Francisco, CA 94130
877 Commanding Officer, RHCU DET 319, Naval Reserve Center, Naval Support Activity, Long Beach, CA 90801
878 Commanding Officer, RHCU DET 419, Naval Reserve Center, Camp Decatur, NTC, San Diego, CA 92133
879 Officer in Charge, Naval Submarine Training Center, Pacific Detachment, 140 Sylvester Road, Ballast Point, San Diego, CA 92106
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881 Officer in Charge, Naval Instructional Program, Development Detachment, Great Lakes, IL 60088
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883 Commandant, US Coast Guard, 400 7th St., SW, Washington, DC 20590
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US Naval Academy, Nimitz Library, Annapolis, MD 21402

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Commanding Officer, Naval Submarine Support Facility, New London, Groton, CT 06340

Commanding Officer, Underwater Demolition Team 22, FPO New York 09501

Chief of Naval Technical Training, Training Coordinator for Diving & Salvage, Naval Air Station, Memphis, Millington, TN 38054

PCO, FRANK CABLE (AS 40), Supervisor of Shipbuilding, Conversion & Repair, USN, Seattle, WA 98115

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--- Repair Officer, USS PROTEUS (AS 19), FPO San Francisco 96646
--- Repair Officer, USS SPERRY (AS 12), FPO San Francisco 96645
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