

# Development of an Antenna Coupler that Fully Compensates the Deficiencies of Electrically Short LF/MF Antennas

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## BIOGRAPHY

John Pinks earned a Higher National Certificate in Electrical Engineering at Portsmouth College of Technology in England in 1960. He worked on early experiments with inertial navigation in the Airborne Research & Development Laboratories of Plessey UK Ltd. before moving to EMI Canada in 1964. At EMI he developed airborne automatic direction finders and ionospheric sounding equipment for military applications in Canada and the USA. In 1969 he joined with two other English engineers in the establishment of a new North American company called Nautel, which quickly established a reputation for world leadership in the development and manufacture of totally solid-state radio transmitters used for navigation, communications and broadcasting. He retired from full time employment in 1998 following 25 years as Chief Engineer but continues to consult to Nautel as the need arises.

## ABSTRACT

Advances in semiconductor technology have made today's transmitters much more efficient than their predecessors. The subsequent reduction in their physical size has made them significantly more susceptible to the effects of mismatch of their terminating impedance that results in increased heat dissipation in their final amplifiers. They usually contain sensors that measure the reflected power and automatically reduce the output power to prevent it from exceeding a safe level.

Transmitting antennas operating in the low and medium frequency bands are usually very short compared to the operating wavelength. This results in an antenna input impedance comprising a large capacitive reactance in series with a low value resistance. Antenna tuning units are used to convert this impedance to the 50 ohms terminating impedance required by the associated transmitter. These usually comprise a large loading coil which is tuned to series resonate the antenna capacitance and a matching device to convert the resulting resistive load to 50 ohms. This arrangement causes the antenna to operate as a narrow band-pass filter that requires continuous automatic tuning of the loading coil inductance. The more stable resistive term has

historically been set for a matched condition using selectable taps during installation.

A number of installations have experienced unacceptable variations of the radiated field strength caused by variations of the antenna equivalent resistance value. This paper describes the development of an Antenna Tuning Unit, which provides automatic adjustment of both the loading coil inductance and the resistive matching network so that an acceptable transmitter terminating impedance is maintained over wide variations of antenna characteristics. An additional feature measures the antenna current and adjusts the transmitter's output power to maintain it and consequently the radiated power at a stable value.

The use of microcontrollers within both the tuning unit and the associated transmitter with serial communication between them provides the ability to remotely monitor the operation of the antenna tuning unit from the location of the transmitter or from any location via a serial connection.

## INTRODUCTION

During the past two decades, radio frequency transmitters such as non-directional radiobeacons and differential GPS transmitters that operate in the low and medium frequency bands have achieved significant improvements in efficiency. This has been made possible by the availability of power MosFet semi-conductors. The final RF amplifiers now operate in the class D (switching) mode with efficiencies exceeding 90% compared to the efficiencies of 50% or less of previously used Class B designs. Hence their cooling surfaces are required to dissipate only 1/5 of the power of older equipment allowing a significant reduction in physical size. It follows that this equipment is much more susceptible to the effects of mismatch and the additional dissipation that results from reflected power when they are connected to imperfectly matched loads. Modern transmitters monitor their reflected power and reduce their output power to prevent it from exceeding a safe level. Under extreme mismatch conditions the transmitter may be forced to shut down completely to prevent equipment damage.

Antennas that are used at LF/MF frequencies comprise vertical structures erected above an arrangement of ground radials to provide a return path for the radiated antenna current. These antennas are usually much shorter than an optimal height because the wavelength at the operating frequency is very long. For example, at a frequency of 300 kHz, the wavelength is 3280 ft. These antennas have input impedances that are far from ideal.

Figure 1 shows the relationship between input impedance and tower height, measured in fractions of the operating wavelength, for typical vertical radiators<sup>[1]</sup>. It can be seen that towers that are typically used, with heights in the order of  $0.04\lambda$  to  $0.1\lambda$ , (130 to 328 ft. at 300 kHz.) exhibit impedances comprising a high capacitive reactance in series with a relatively low resistance value.

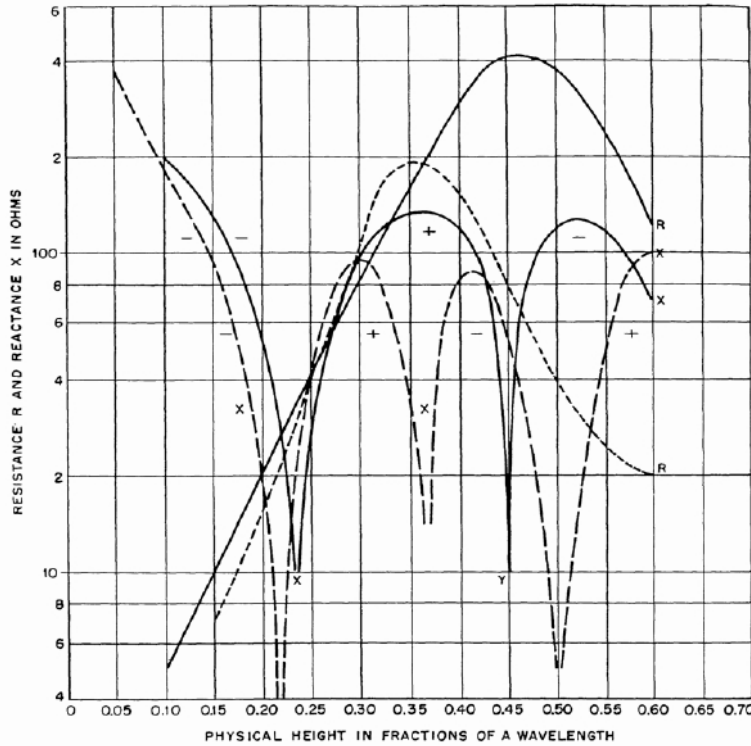


Figure 1-Resistance and Reactance components of impedance between tower base and ground of vertical radiators. Solid lines show average values for guyed towers and dashed lines for self-supporting towers.

The equivalent circuit of a typical antenna<sup>[2]</sup> is shown in Figure 2. It comprises the antenna capacitance in series with several resistances. These resistances represent the radiation resistance ( $R_R$ ), determined by the degree to which the antenna couples to the 377 ohm impedance of free space, connected in series with two resistive loss components. These include the equivalent antenna series resistance ( $R_A$ ) that results primarily from insulator leakage currents and the ground resistance ( $R_G$ ) representing radio frequency losses in the ground beneath the antenna.

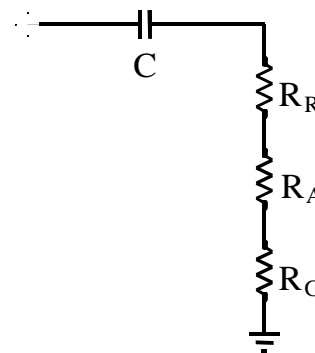


Figure 2 - Equivalent circuit of Antenna

The process of converting this impedance to the stable, purely resistive, 50 Ω impedance required by the transmitter and achieving sufficient antenna bandwidth can present technical difficulty.

A commonly used technique resonates the antenna capacity using a high power variable inductance that is

continuously maintained in a tuned condition by a servo system. The resulting low resistance component is then transformed to 50Ω using a tapped RF transformer that is set up during initial installation. Figure 3 shows the overall equivalent circuit for the antenna and the tuning unit.

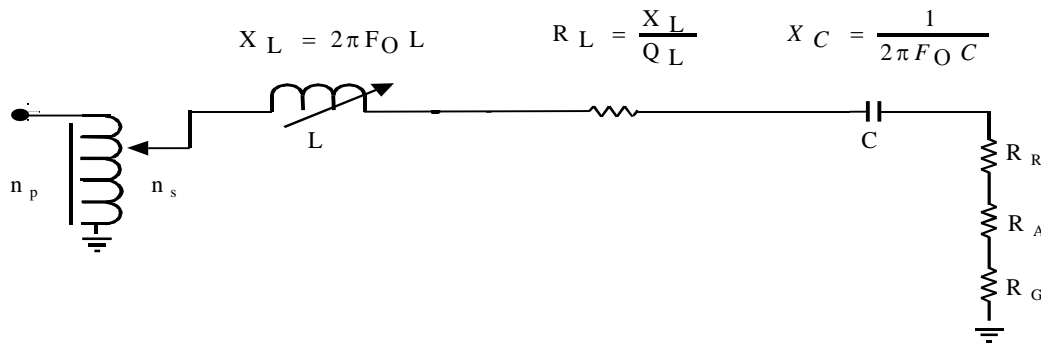


Figure 3 – Equivalent Circuit of Antenna Tuning Unit and Antenna.

The inductance of the loading coil is adjusted to resonate with the antenna capacitance at the operating frequency  $F_0$ . The loss resistance of the loading coil adds an additional resistance  $R_L$

Where

- $C$  = Antenna Capacitance in Farads
- $R_A$  = Antenna Loss Resistance in Ohms
- $R_G$  = Ground Loss Resistance in Ohms
- $R_R$  = Radiation Resistance in Ohms
- $L$  = Loading Coil Inductance in Henries
- $R_L$  = Loading Coil Series Loss Resistance in Ohms

At Resonant Frequency  $F_0$  where  $|X_L| = |X_C|$

$L = 1 / ((2\pi F_0)^2 C)$  Henries

Loading Coil Loss Resistance ( $R_L$ ) =  $X_L / Q$

Where  $Q$  is the quality factor of the loading coil. Total

Resistance  $R_T = R_A + R_G + R_R + R_L$

The required 50Ω input impedance is obtained when the matching transformer primary to secondary turns ratio ( $N$ ) is equal to  $\sqrt{50/R_T}$

Then

$$\text{Radiated Power } P_R = I_A^2 \times R_R \text{ watts} \quad (1)$$

$$\text{Antenna Current } I_A = \sqrt{(P/R_T)} \text{ amperes} \quad (2)$$

Total Power lost as heat

$$P_{\text{diss}} = I_A^2 (R_A + R_G + R_L) \text{ watts} \quad (3)$$

$$\text{Efficiency } \eta = R_R / R_T \quad (4)$$

Where the Radiation Resistance<sup>[2]</sup> is given by

$$R_R = 160 \pi^2 (H_e / \lambda)^2 \text{ ohms} \quad (5)$$

In these equations

$P$  = Input Power to Tuning Unit in watts.

$H_e$  = Effective height of the antenna.

$\lambda$  = Wavelength at Frequency  $F_0$ .

Both  $R_A$  and  $R_G$  are subject to change caused by environmental conditions. Variation of the resistive term mismatches the transmitter and, if a critical reflected power threshold is exceeded, causes it to reduce its output power. In addition, even if the transmitter power remains constant, changes of loss resistance values cause a variation of antenna efficiency and hence variation of the radiated power. Seasonal re-adjustment of the matching transformer and the transmitter output power is often necessary. In some situations, more frequent resistive changes have resulted in persistent unacceptable variations in the radiated field strength.  $H_e$  and hence  $R_R$  are related to the physical height and configuration of the antenna and hence have a relatively stable value. It can therefore be seen from Equation (1) that stabilization of the antenna current will result in a stable radiated power and field strength.

#### PROJECT OBJECTIVE

The objective of this engineering project was to develop a three kilowatt antenna tuning unit, capable of operation at frequencies between 190 and 535 kHz., which could mitigate these changes of the antenna's resistive components and achieve a stable antenna current. This was to be achieved by replacing the manually selectable matching transformer by a continuously variable resistive matching circuit, which could be controlled by sensors to maintain the input resistance at 50Ω. Having stabilized the input resistance, a feedback loop would be used to

adjust the transmitter power level to maintain a constant antenna current. Analysis of the equivalent circuit of Figure 3 shows that a 2:1 increase in the value of the total antenna resistance ( $R_T$ ) would require a 2:1 increase in the transmitter output power. Hence a transmitter with a sufficiently high maximum power rating would be required.

### THEORETICAL BASIS FOR RESISTIVE MATCHING UNIT

The approach that was investigated is based upon the use of a pair of tuned, mutually coupled coils, between which the coupling factor  $k$  can be varied. Figure 4 shows the circuit diagram of this arrangement. The inductances of the primary ( $L1$ ) and secondary ( $L2$ ) windings of the mutually coupled coils are equal and are tuned for series resonance at the operating carrier frequency by equal capacitors  $C1$  and  $C2$ . The equivalent circuit is shown in Figure 5.

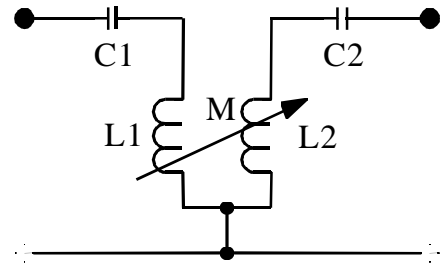


Figure 4 Circuit Diagram of Resonant Mutually Coupled Coils

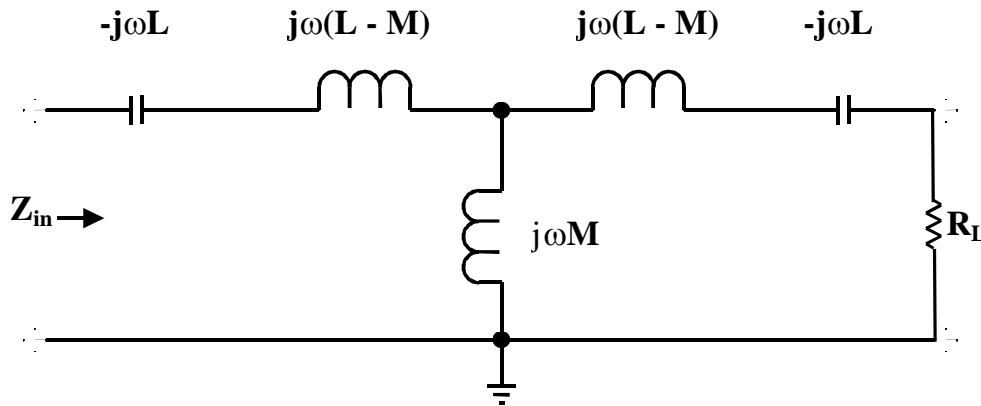


Figure 5 Equivalent Circuit of a pair of mutually Coupled Coils

Where

$$j = \sqrt{-1}$$

$\omega$  = Angular velocity of the input frequency in radians per second.

$C$  = Capacitor value of  $C1$  and  $C2$  in Farads

$L$  = Inductance of both  $L1$  and  $L2$  in Henries

$M$  = Mutual inductance between  $L1$  and  $L2$  in Henries.

$R_L$  = Resistance connected to the output terminals

$Z_{in}$  = Impedance seen at the input terminals.

The Mutual Inductance  $M$  is given by the expression

$$M = k \sqrt{L1L2}$$

Where  $k$  = Coupling coefficient.

As  $L1=L2$ , this simplifies to

$$M = kL$$

An analysis of this circuit shows that the input impedance ( $Z_{IN}$ ) is given by the expression

$$Z_{IN} = (k^2 X_L^2) / R_L \quad (6)$$

Where  $k$  = Coefficient of coupling between the coils.

$X_L$  = Reactance of both the primary and secondary coils

Equation (6) shows that, providing the primary and secondary coils remain resonant, the load resistance can be transformed to a purely resistive input resistance in proportion to the value  $k^2$ .

Inquiries to existing users of this type of equipment including the Federal Aviation Administration, the United States Coast Guard and Nav Canada suggested that overall resistance variations of 2:1 could be expected.

Hence a minimum variation of  $k$  of at least  $\sqrt{2}$  or 1.41 : 1 would be required.

The equivalent circuit of Figure 5 can be further simplified to that shown in Figure 6. This configuration is a classical T section,  $\lambda/4$  transformer with its inherent  $90^\circ$  phase shift between input and output.

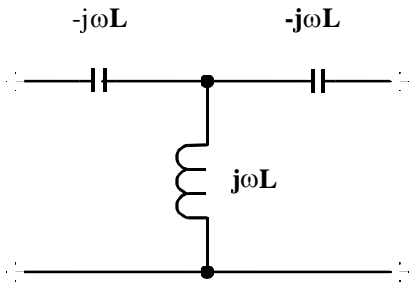


Figure 6 Simplified equivalent circuit of a Pair of Resonant mutually coupled coils

### EXPERIMENTAL MUTUALLY COUPLED COILS

A photograph of an experimental pair of mutually coupled coils is shown in Figure 7.

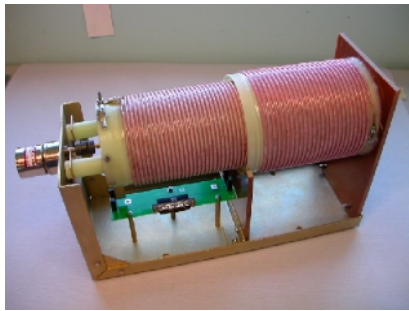


Figure 7 – Experimental Mutually Coupled Coils

The outer coil is wound using 12 AWG Litz wire on a 3 3/4 inch diameter former. The smaller coil uses the same wire with a slightly smaller pitch to achieve the same inductance and the same physical length on a 3 inch former. The small coil is inserted coaxially into the larger coil using a small brass lead screw driven by a reversible dc motor. Optical limit switches are provided to limit the range of travel. This arrangement yielded extremely low losses and a k value that varied between 0.33 and 0.75. Hence the term  $k^2$  varied from 0.109 to 0.56 i.e. providing an overall resistance variation exceeding 5:1.

As shown in equation (6), the input impedance is also proportional to the value  $X_L^2$ . Hence for a fixed value of inductance the reactance  $X_L$  varies with frequency. Although the transmitters involved operate at a fixed frequency, this could be anywhere in the range 190 to 535 kHz. Provision of a constant  $X_L$  value over this range would require multiple taps on the coupled coils, which would be somewhat impractical. It was decided instead, to use a fixed inductance value of 46 micro-henries and to standardize the value of the term  $X_L^2 / R_L$  at 178.6 by selecting an appropriate  $R_L$  value to suit operating frequency. The value of  $R_L$  is selected using fixed taps on a conventional matching transformer, which is set up at

the time of installation, to suit the particular antenna and operating frequency. This produces a fixed nominal value of k throughout the full frequency range. Interpolation between the discrete matching transformer settings is easily accommodated by the wide variation of k available from the coupled coils. A photograph of the matching transformer is shown in Figure 8.

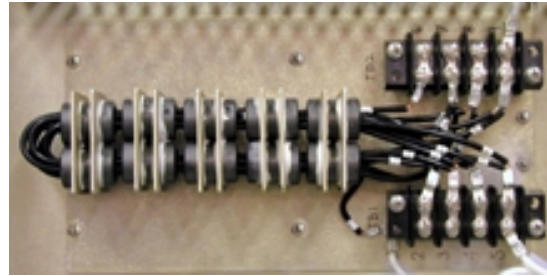


Figure 8. Matching Transformer

Table 1 shows the value  $X_L$  and the required value of  $R_L$  over the complete frequency range. It also shows the required value of the capacitor  $C_1$  needed to tune with the 46 micro-henries of the coupled coils.

Table 1 – Required values of  $X_L$ ,  $R_L$  and  $C_1$

FREQ KHz	$X_L$ uH	$R_L$ ohms	$C_1$ Pico-farads
190	54.91	16.88	15250
200	57.8	18.77	13760
225	65.03	23.62	10877
250	72.26	29.24	8810
275	79.48	35.37	7281
300	86.71	42.1	6118
327	94.51	50.02	5149
330	96.25	52.05	5060
350	101.16	57.31	4495
375	108.31	65.69	3916
400	115.61	74.85	3442
425	122.83	84.48	3048
450	130.06	94.72	2719
475	137.29	105.55	2440
500	144.51	116.94	2202
525	151.73	128.92	2932
535	154.63	133.89	1923

High power, variable capacitors, with this capacitance range are not readily available. Instead, a set of six fixed capacitors is used. Individual capacitor values are chosen in a binary sequence equal to C, 2C, 4C, 8C, 16C and 32C where C=218 pico-farads. When selectively connected in parallel, this allows a total of 63 possible combinations, in increments of 218 pico-farads to be obtained. The requirement to tune the secondary coupled coil is actually

eliminated by the fact that its load comprises a resonant circuit consisting of a loading coil and the antenna capacitance. A photograph of the primary tuning capacitors is shown in Figure 9.

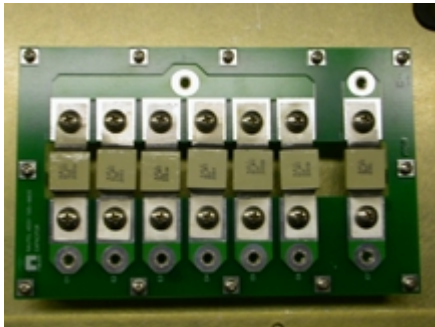


Figure 9. Primary Tuning Capacitors

#### EXPERIMENTAL LOADING COIL

For many years Nautel tuning unit designs have used a pair of solenoid shaped loading coils, wound with solid copper wire, one in a clockwise and the other in a counter clockwise direction with a selection of tapping positions. The coils may be connected either in series or in parallel thus providing a wide choice of the total inductance. When they are mounted side by side this technique tends to confine the magnetic field to a tight doughnut shape as compared to the extensive uniform field that is produced by a single solenoid. Hence the size of the aluminum enclosure can be reduced without causing excessive eddy current losses in the cabinet and a resultant lowering of the operating Q value.

Accurate tuning has been accomplished using a cylindrical copper slug that is moved coaxially in and out of one of the coils to achieve a +/- 10% inductance change. This method has yielded loading coil Q values of approximately 250. The resulting coil loss resistance has had a significant effect upon both the overall antenna efficiency and the temperature rise of the coils and copper slug. The use of Litz wire, which contains multiple strands of insulated wires, to reduce both the rf resistance and eddy current losses in the coils has not previously been considered worthwhile due to the Q degrading effect of the copper tuning slug. As part of this project, the advantages of using Litz wire were investigated. The copper tuning slugs were replaced by the use of a variometer. This consists of small coil, connected in series with one of the main loading coils, and positioned inside that coil near one end such that mutual coupling exists between them. The small coil is rotated on a motor-driven shaft, such that the coil's axis can be moved from a position that is coaxial to the main coil to a position at right angles to it. The full range of rotation also includes a position that is coaxially in opposition to the main coil. Optical sensors are used to limit the range of travel to  $\pm 90$  degrees.

This arrangement yields a total inductance variation given by the expression <sup>[4]</sup>

$$L_{\text{tot}} = L_1 + L_2 \pm 2 L_m$$

Where

$L_1$  = Inductance of the main coil

$L_2$  = Inductance of the moving coil

$L_m$  = Mutual Inductance between them

The axial distance between the centers of  $L_1$  and  $L_2$  controls the value of  $L_m$  and hence the amount of variation available. Figure 10 is a photograph of the main coil with its moving coil partially rotated.

The tuning unit is designed to operate over the frequency range 282 to 495 kHz, with antenna capacitance values from 600 to 3500 pico-farads. Hence the required inductance range varies widely from 26 to 530 micro-henries. For NDB applications the frequency range is 190-535 kHz., hence a different coil set is required. The tuning unit utilizes two main loading coils that are identical except that one is wound in a clockwise direction and the other counterclockwise. Only one contains a mutually coupled rotating coil. Each main coil must therefore contribute approximately 265 micro-henries. The minimum value of 26 micro-henries is achieved by a parallel connection using a small section of each coil. If the same tap is selected on each coil, the magnetic field is constrained as described above. The relative position of the two coils is shown in Figure 11. Connections to the coils are made using brass clamp at points on the coils where the individual strands of the Litz wire are soldered together. The tap where the moving coil connects in series with the main coil is chosen such that  $\pm 90$  degree rotation produces  $\pm 5\%$  change in the total inductance.



Figure 10. Main Coil with Moving Coil Rotated 45 degrees.



Figure 11. Loading Coil Assembly

The Q value of this loading coil assembly was measured to be in the range of 500 to 600. This significantly increases the efficiency of antenna / tuning unit combination compared to the equipment previously supplied by Nautel. With some short antennas, operating at the lower end of the frequency band, this may result in an inadequate antenna bandwidth. This antenna deficiency may be overcome by the inclusion of an additional power resistor at the point where the tuning unit connects to the antenna's ground radial system. Nautel offers an 1800 watt resistance network that may be adjusted for a range of resistance values between 1 and 5 ohms for this purpose.

A block diagram of the complete Antenna Tuning Unit is shown in Figure 12.

The unit contains a dc power supply, powered from a 115 or 230 volt ac supply, which provides 5 volts dc for a microcontroller and 22 volts dc for operating two bi-directional motors.

The input from the transmitter (1) is sampled by voltage probe (2) and current probe (3) which produce dc voltages proportional to the rf signals. Phase detector bridge (4) produces a dc error signal on one of two outputs when the phase angle between the input current lags or leads the voltage. Tuning Capacitor (5), which comprises six fixed capacitors, is set up on installation to suit the operating frequency. Matching transformer (8) is adjusted during installation to produce the value  $R_L$  to suit the operating frequency as listed in Table 1. A direct path is provided from the output at the high voltage insulator to ground via the loading coil, the antenna current probe and the matching transformer. Hence static energy is discharged from the antenna without the use of a static drain choke. Microcontroller (11) controls two bi-directional motors to tune the loading coil assembly and adjust the mutually coupled coils to maintain a purely resistive,  $50 \Omega$  input impedance. A front panel meter provides a direct indication of Forward Power, Reflected Power and Antenna Current. The meter indications derive energy from the actual rf signal, hence are not dependent upon dc

supplies. When local operating mode is selected, front panel controls allow the following push button selections:

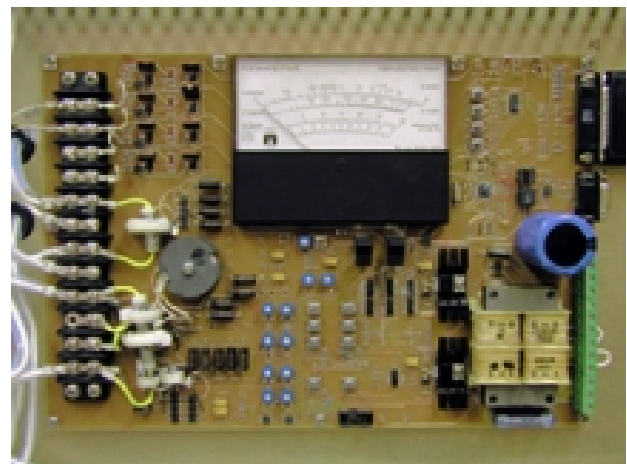
- Slew Tuning motor in either direction
- Slew Matching motor in either direction
- Inhibit auto operation of Tune Control
- Inhibit auto operation of Matching Control
- Transmitter ON/OFF
- Tune Setup

When Remote Control is selected at the front panel, these same control functions are available from the location of the transmitter. The ability to switch off the transmitter and apply an input shorting safety link is also available within the tuning unit. Front panel indicator lamps are provided to fully indicate equipment status including the direction of any mistune or mismatch condition.

Current Probe (9) produces a dc voltage proportional to the mean value of the antenna current, which is monitored by Microcontroller (11). An RS485 serial communication link feeds this information back to the transmitter. A second Microcontroller (14) located in the transmitter, adjusts the transmitter output power to maintain the antenna current at a preset value. This feature is inhibited when a mistune or mismatch condition exists and the automatic adjustment process is taking place or when the slew buttons are being actuated. A fundamental requirement for this system is to use a transmitter that has a remote power adjustment capability and an adequate maximum output power level.

Photographs of the Antenna Tuning Unit, with the front cover removed, are shown in Figure 13.

The Control/Monitor printed wiring board, which



contains all of the controls, indicator lamps and the Test Meter is shown in Figure 14.

Figure 14 Control/Monitor PWB

Figure 15 shows the high voltage insulator which is manufactured using Teflon to minimize the effect of environmental pollution and the solid brass adjustable spark balls used to protect the unit from the damaging effects of lightning.

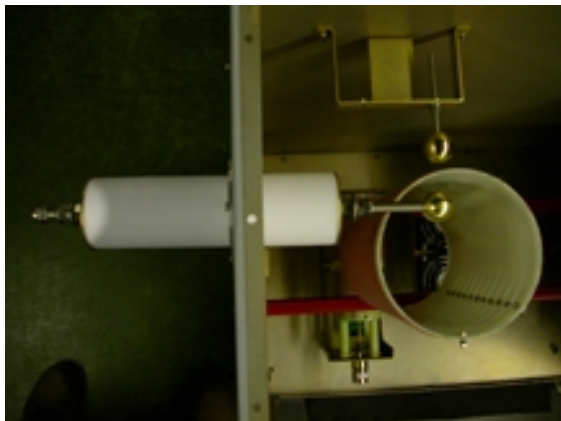


Figure 15 High Voltage Insulator and Spark Balls

#### EXPERIMENTAL RESULTS

A prototype Antenna Tuning Unit has been extensively tested in the laboratory using dummy antenna loads from 600 –3500 pico-farads and 2-20 ohms over the frequency range 282 - 495 kHz.

Operation at power levels as low as 50 watts were investigated to ensure adequate sensitivity of the automatic tuning and matching systems. Tests at power levels up to 3 kilowatts were conducted to subject the equipment to maximum electrical component stress and temperature rise.

The unit was able to rematch step function changes of the total antenna resistance by as much as 50% within a period of 60 seconds to a condition where the reflected power was too low to measure. Antenna current variations were less than  $\pm 1.5\%$  at high power levels and  $\pm 2.5\%$  at the lower power extremes.

Field-testing of three beta systems is scheduled to commence in June 2004.

#### SIGNIFICANCE OF THE PROJECT

Utilization of this technology can significantly reduce the field strength variations that are currently being experienced with both radio beacon and DGPS systems transmission systems. This could allow a far higher confidence level in meeting the required range and signal availability.

Remote monitor and control features in the coupler will allow most post-installation maintenance procedures to be conducted from the location of the transmitter. This will greatly simplify compliance with national safety standards

such as IEEE C95.1-1999 and Safety Code 6 by protecting maintenance personnel from harmful electromagnetic fields that exist close to the tuning unit and the antenna.

The same remote monitor and control features can be made available from any location via a serial connection, greatly enhancing maintenance and user support activities.

Nautel has been awarded a U.S. Patent entitled "Automatic Matching and Tuning Network" covering the use of mutual coupled coils for resistive matching. A second U.S. Patent application entitled "Automatic Matching and Tuning Unit" (Docket No.50026-026), which refines the circuit details and includes the antenna current stabilization technique, has been submitted.

#### ACKNOWLEDGEMENTS

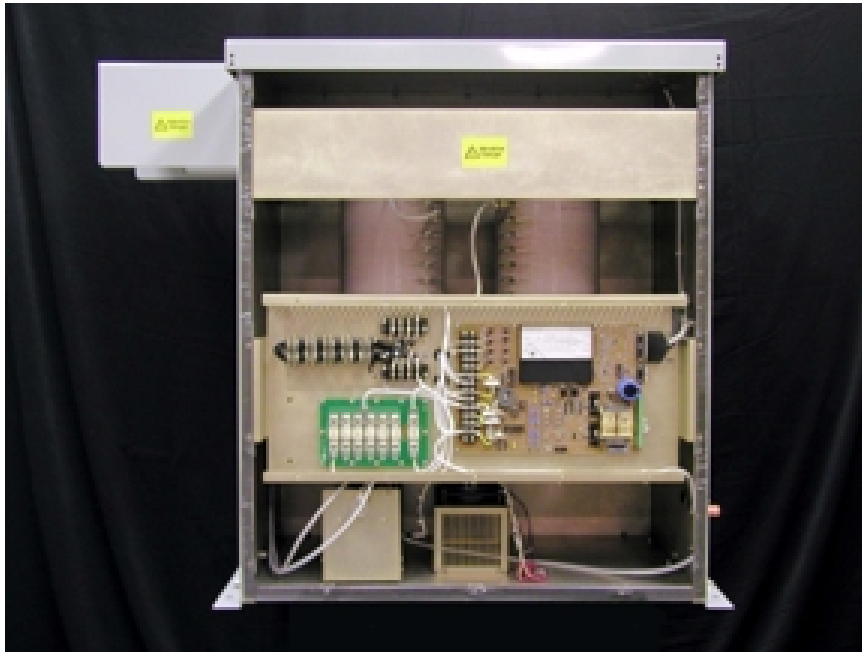
I would like to acknowledge the assistance of Dennis Covill of Nautel whose original suggestion led to the use of mutually coupled coils for this purpose.

I appreciate the input from LTJG Chris Treib from USCG Command and Control Center (C2CEN) regarding the type and characteristics of the antennas used with the DGPS System.

#### REFERENCES

1. "Reference Data for Radio Engineers" Howard W. Sams Co., Inc., 1975
2. Hagaman, B. "Antenna Engineering Handbook." McGraw Hill, 1961
3. Terman, F. E. "Radio Engineers Handbook." McGraw Hill Book Co., Inc., 1943.
4. Terman, F. E. "Radio Engineers Handbook." McGraw Hill Book Co., Inc., 1950.





Front View



Side View

Figure 13 Antenna Tuning Unit