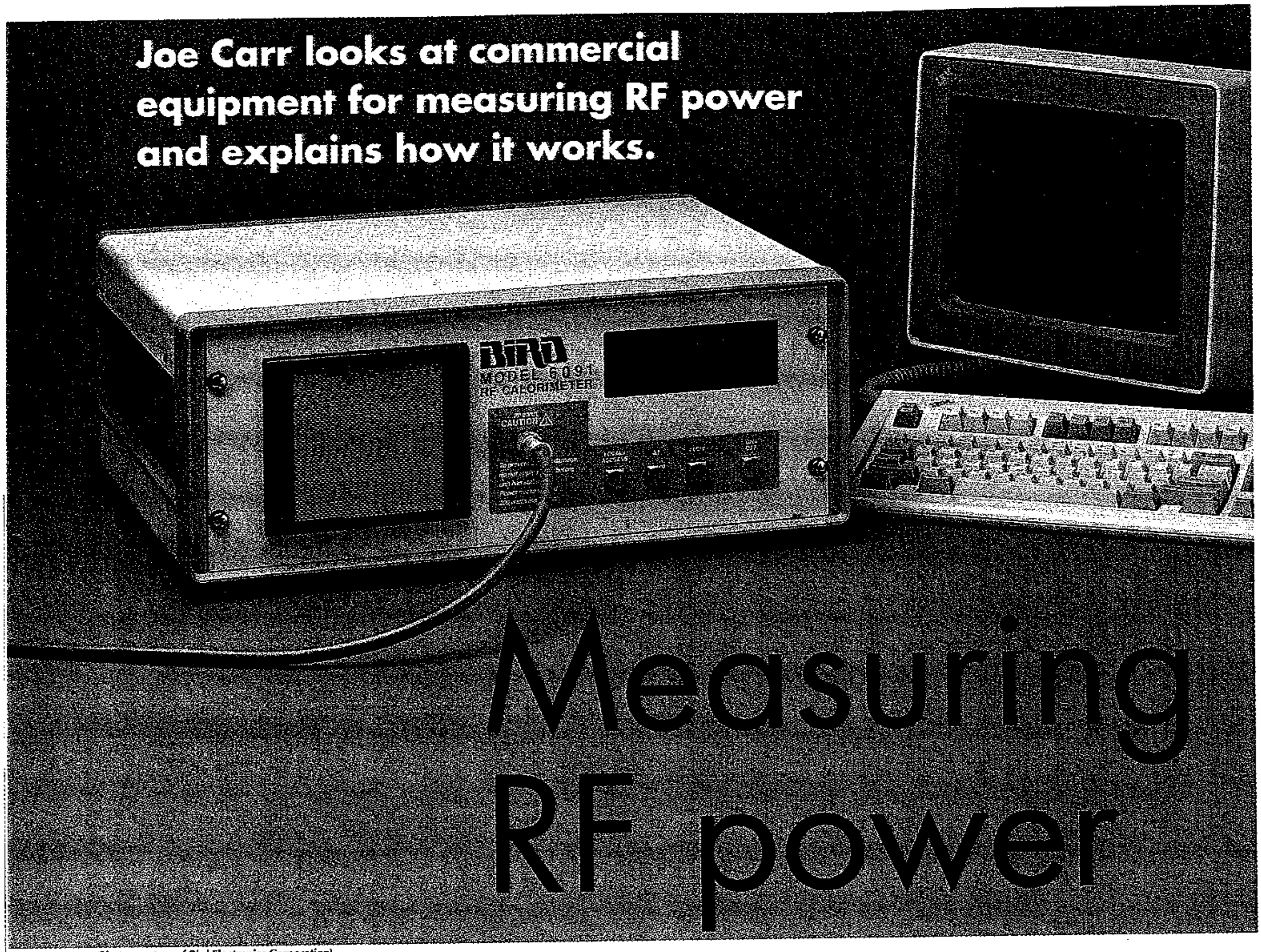
Measuring RF power

Joe Carr looks at commercial equipment for measuring RF power and explains how it works.



(Photo courtesy of Bird Electronics Corporation)

Here I take a look at some popular commercial products, as well as the calorimetry approach to high power measurements, and some methods for making low power measurements. Error and uncertainty sources in RF power measurements are discussed too, later in the article.

The Bird 'Thruline' sensor

Bird Electronics' Thruline sensor is shown in **Fig. 1a)**, while an equivalent circuit is shown in Fig. **1b)**. The sensor consists of a coaxial transmission-line section, and a wire-loop directional coupler that connects to a diode detector, D_1.

Consider the equivalent circuit in Fig. 1b) The factor M is the mutual coupling between the loop and the centre conductor of the coaxial line section, as well as the voltage divider consisting of R and C.

Potential E is the voltage between the inner and outer conductors of the coaxial line, while E_R is the voltage drop across the resistor, e_M is the voltage across the inductor and e is the output potential.

Voltage divider R/C produces a potential given by equation (1), provided that $R<<X_C$ and $e_m=Ij\omega\pm M$

$$e_r = \frac{RE}{X_C} = REj\omega C \qquad (1)$$

The output voltage is,

$$e = e_R + e_M = j\omega(CRE \pm MI) \qquad (2)$$

Values of the components are selected such that $R<<X_C$ and $CR=M/Z_o$ It is now possible to state that the DC output voltage is,

$$e = j\omega\left[\frac{EM}{Z_o} \pm MI\right] = j\omega M\left(\frac{E}{Z_o} \pm I\right) \qquad (3)$$

At any point along a transmission line the voltage appearing between the centre conductor and outer conductor E is a function of forward voltage E_F and the reflected voltage E_R.

By combining equations, it is evident that when the directional coupler is pointed at the load, the output voltage of the sensor reads the forward voltage, and produces an output voltage of,

$$e = \frac{j\omega ME_F}{Z_o} \qquad (4)$$

And when pointed at the source,

$$e = \frac{j\omega ME_R}{Z_o} \qquad (5)$$

Thus, this sensor produces a voltage that is a function of the direction of the RF signal flowing in the transmission line.

Figures 2 and **3** show two examples of Thruline instruments. The one in Fig. 2 is the Model 4410A. It is based on the classic Model 43 design*. It offers an insertion voltage-standing-wave ratio of 1.05:1 up to 1GHz.

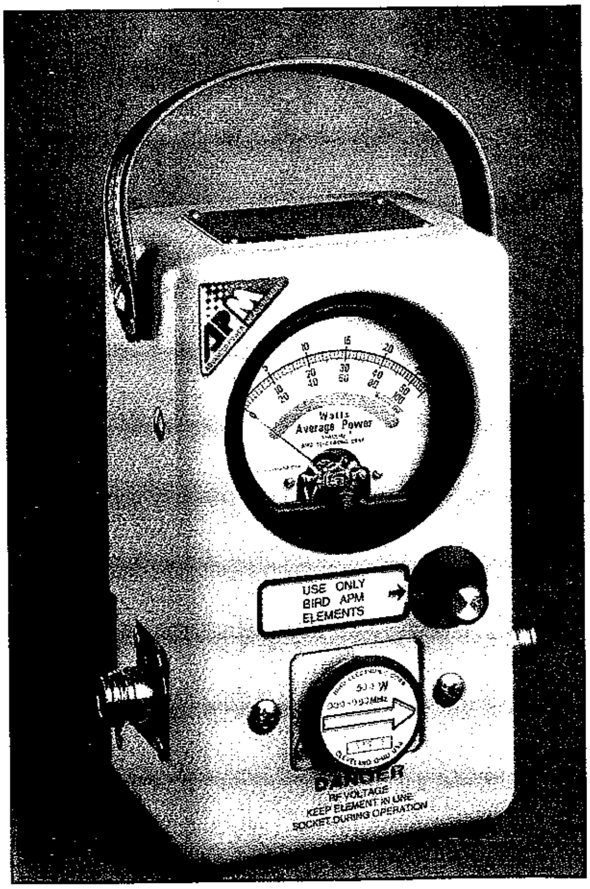
The sensor elements are plug-in. Each element has an arrow on it to indicate the direction of the measurement – pointed towards the load or the source, depending on whether you measure P_F or P_R. Once you know P_F and P_R, you can computer the VSWR from equation (6),

$$VSWR = \frac{1+\sqrt{\frac{P_R}{P_F}}}{1-\sqrt{\frac{P_R}{P_F}}} \qquad (6)$$

One difference between this instrument and earlier instruments is that there is a calibration factor control on the meter to optimise performance for the specific sampling element inserted.

The Bird APM-16 Advanced Power Meter is shown in Fig. 3. This meter is similar in concept to the older Model 43, but is considerably advanced. While the Model 43 measures RMS CW power, the APM-16 will measure analogue and digital complex waveforms, as well as CW – for example CDMA, TDMA, FDMA, COFDM and other modulations. It will measure both peak and RMS power levels.

Figure 4 shows a different approach. This meter uses a remote sensor head connected in-line between the source and load, and a multi-range digital readout display. It also has a computer interface that will permit running power-versus-frequency curves.



Calorimeters

Calorimeters are capable of making very accurate measurements of RF power – especially at high power levels where other methods tend to fall down. These instruments measure the heating capability of the RF waveform. In this way, they produce an output proportional to the RMS power level that is independent of the applied waveform.

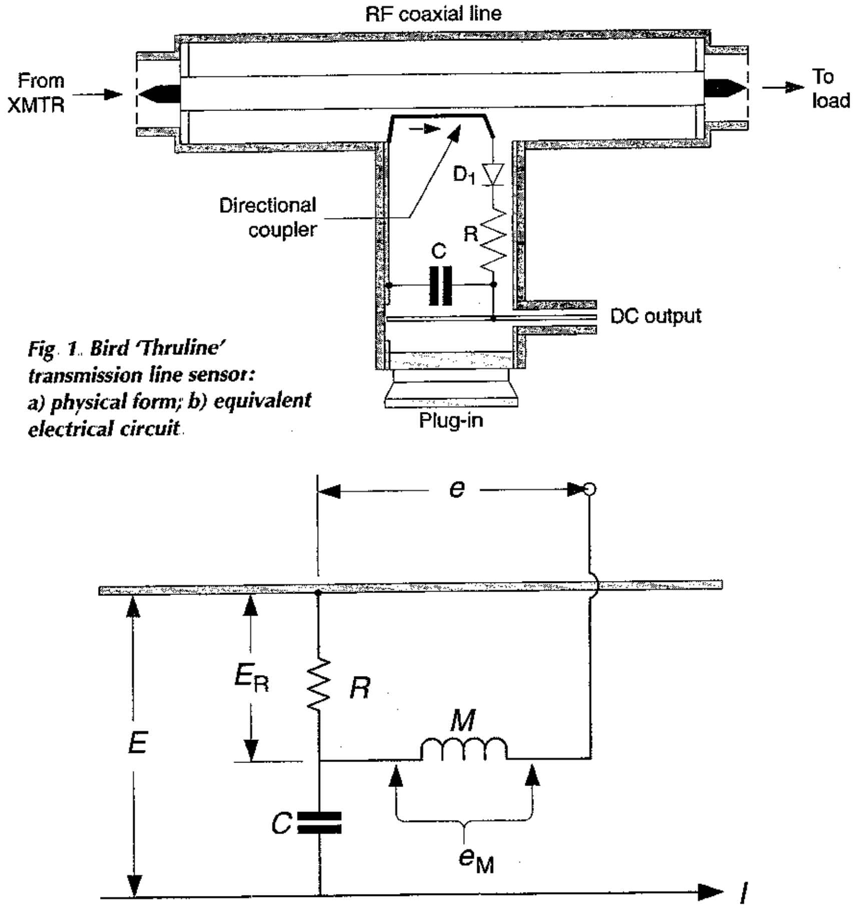


Fig. 1. Bird 'Thruline' transmission line sensor: a) physical form; b) equivalent electrical circuit.

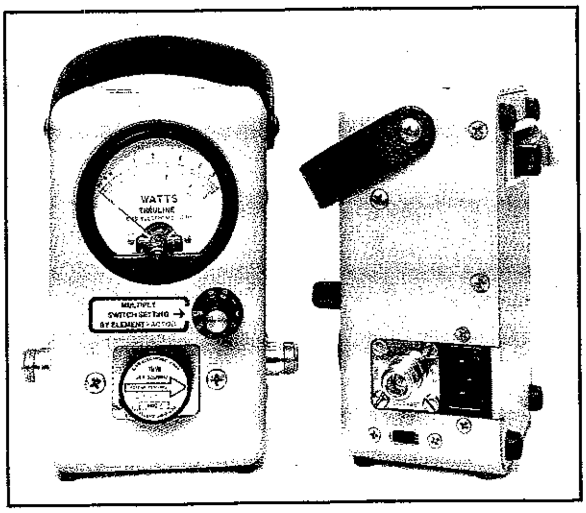


Fig. 2. Bird Model 4410A RF wattmeter. Photo courtesy Bird Electronics Corporation.

Fig. 3. Bird Model APM-16 RF wattmeter. Photo courtesy of Bird Electronics Corporation.

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* My Model 43 has been banging around my toolkit for about 30-years and still works well.

The First Law of Thermodynamics[†] is the basis for the operation of calorimeters: energy can neither be created nor destroyed, only changed in form.

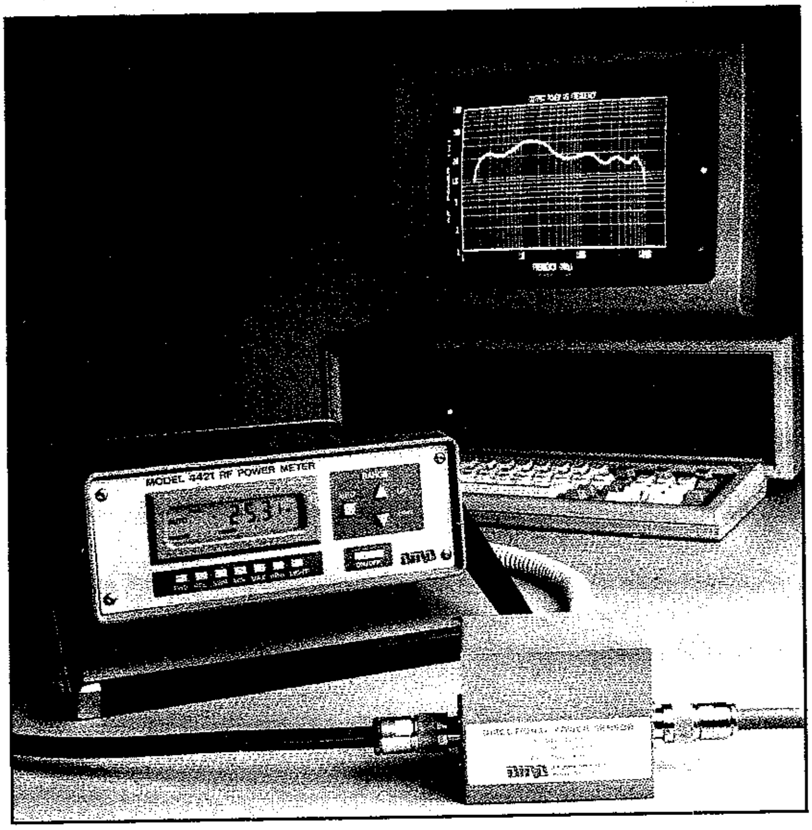
There are two basic forms of RF power calorimeter: dry and flow (or wet). Dry calorimeters are used at lower power levels, and are represented by the thermistor and thermocouple methods discussed in last month's article. Flow calorimeters are used at higher power levels.

Flow calorimeters come in two varieties: substitution flow and absolute flow. Power can be measured using the following relationship,

$$P = F_{mass} \times (T_{out} - T_{in}) \times C_P(T) \tag{7}$$

where P is the power level, F_{mass} is the mass flow rate of the fluid used in the calorimeter, T_{OUT} is the fluid temperature after being heated by the RF load resistor, T_{IN} is the fluid temperature before being heated by the RF load resistor and $C_p(T)$ is the fluid specific heat as a function of temperature T.

Fig. 4. Bird Model 4421 RF power meter with remote sensor head. Photo courtesy of Bird Electronics Corporation.



Substitution-flow calorimeters. This form of RF power meter, Fig. 4, uses two fluid loops. Each fluid loop is heated by a separate termination resistor. Termination 'A' is heated by a low-frequency AC power source, and the power applied to this termination is measured by an AC power meter. The unknown RF power is applied to termination 'B'. The differential temperature, $T_{OUT}-T_{IN}$, is measured by a differential thermocouple.

When the temperatures of the two fluids are equal to each other, then the output of the thermocouple is zero. When the AC power is adjusted to balance the temperatures while RF is applied, producing a zero output voltage from the thermocouple, the RF power is equal to the more easily measured AC power. A temperature stabiliser and heat exchanger returns the temperature of the fluid to base level after it is used to measure power.

This method will produce error of 0.28 percent or better, up to RF power levels of one kilowatt. Both water and oil are used as fluid coolants in various instruments.

Absolute-flow calorimeters. **Figure 6** shows the absolute flow calorimeter. This type of RF power meter measures the mass flow rate of the coolant, as well as the temperature before the RF load resistor, T_{IN}, and after it, T_{OUT}. The mass flow rate is,

$$F_{mass} = f \times W_S(T_{IN}) \tag{8}$$

where W_S is the specific weight of the fluid at the input temperature and f is the volume flow rate (litres/min). All other terms are as previously defined.

Combining equations gives the equation for measuring RF power by this means,

$$P = k \times f \times W_S(T_{IN}) \times C(T_{AVE}) \times (T_{OUT} - T_{IN}) \tag{9}$$

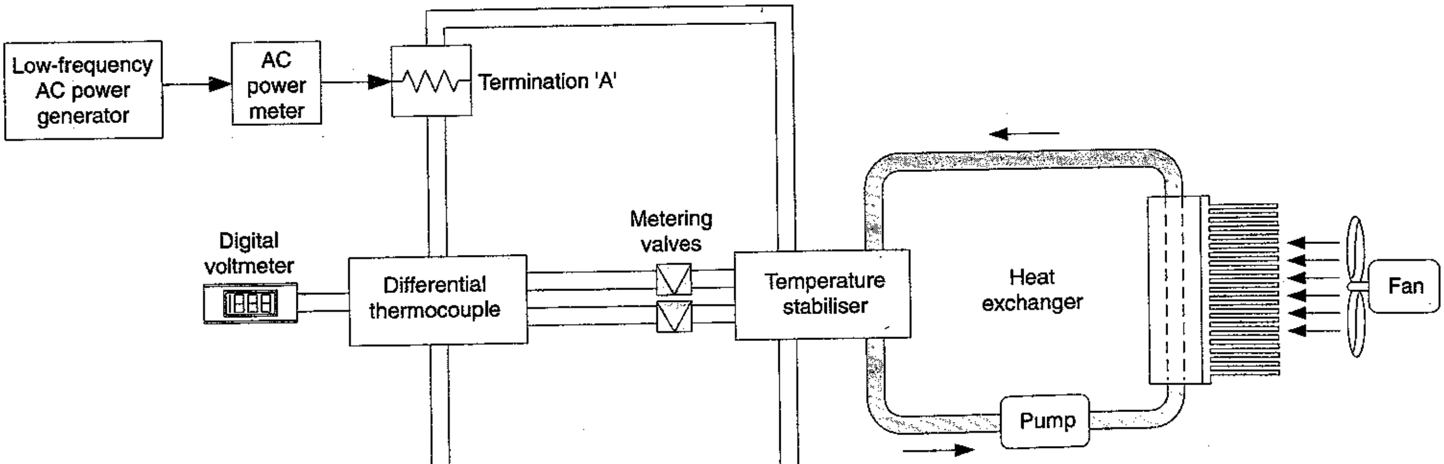


Fig. 5. Substitution flow calorimeter involves two loops, one with known LF power applied, the other subjected to RF power to be determined. LF power is adjusted until output from the differential thermocouple reads zero, at which point, the known and unknown power inputs are equal.

[†] I am told that numbering of the laws of thermodynamics differs in various parts of the world. In the USA we start with the "0th law"

Here, T_{AVE} is $(T_{OUT}-T_{IN})/2$ and all other terms are as previously defined.

One of the advantages of the absolute flow approach is that it does not depend on nulling or calibration of a low frequency power source, yet it produces good accuracy at high power levels up to 80kW.

Figure 7 shows a commercially available calorimeter RF power meter made by Bird Electronics Corporation

Micropower and low-power measurements

At very low power levels the diode output voltage drops very low. At –70dBm for example, the diode produces about 50nV output potential. This level is too close to the noise and drift values of typical DC amplifiers to be useful. A solution is to use a chopper circuit, **Fig. 8.**

A chopper is an electronic switch that turns the DC signal from the diode output on and off at a high rate – typically 100 to 10 000 times per second. Either a square wave or sine-wave 'carrier' applied to the toggle input of the electronic switch creates the switching action

The chopped signal is essentially an AC signal, so it can be amplified in an AC amplifier, which has a much smaller feedback-controlled drift than a DC amplifier. Also, the AC signal can be band-pass filtered to remove noise. The band-pass filter is centred on the frequency of the carrier oscillator.

The chopped, amplified and filtered signal is applied to a synchronous detector that is controlled by the same carrier oscillator that performed the chopping action. A low-pass filter following the synchronous detector removes residual components of the switching action at the carrier frequency. Finally, a DC amplifier provides scaling to the correct DC level, or as level translation for an analogue-to-digital converter.

Micropower measurements pose special problems because they are made at levels below the range of most practical RF power sensors. In some cases, the chopper approach can be used with a diode detector. At lower levels, however, some other method is needed.

Figure 9 shows a comparison method using a calibrated RF signal generator. The instrument selected must have a calibrated output attenuator that provides accurate outputs in dBm or microvolts.

The signal generator and the unknown micropower source are connected to a receiver equipped with an S-meter through a hybrid coupler. The coupler must have either equal port-to-port losses for the two inputs, or at least accurately known different losses.

Optional calibrated step attenuators are also sometimes used to balance the power levels. The receiver acts as a micropower wattmeter or voltmeter because it will produce an S-meter reading of even very weak signals.

Two methods can be used, namely 'equal deflection' or 'double deflection'. In the equal-deflection method, the unknown source is turned on, and the S-meter reading noted. The unknown source is then turned off, and the signal generator is turned on.

Next, the output of the signal generator is adjusted to produce the same S-meter deflection. The power level of the unknown source is therefore equal to the calibrated signal generator output level

The double deflection method sets the signal gen-

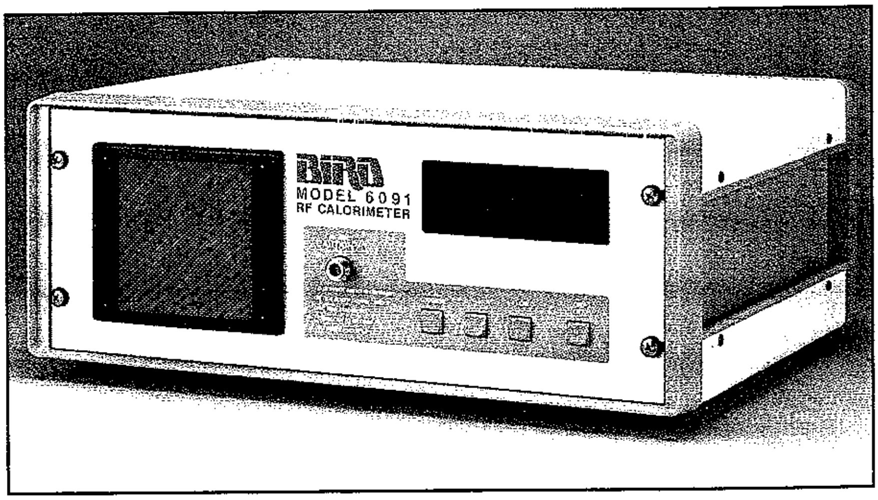


Fig. 7. Bird calorimeter RF wattmeter (Photo courtesy of Bird Electronics Corporation).

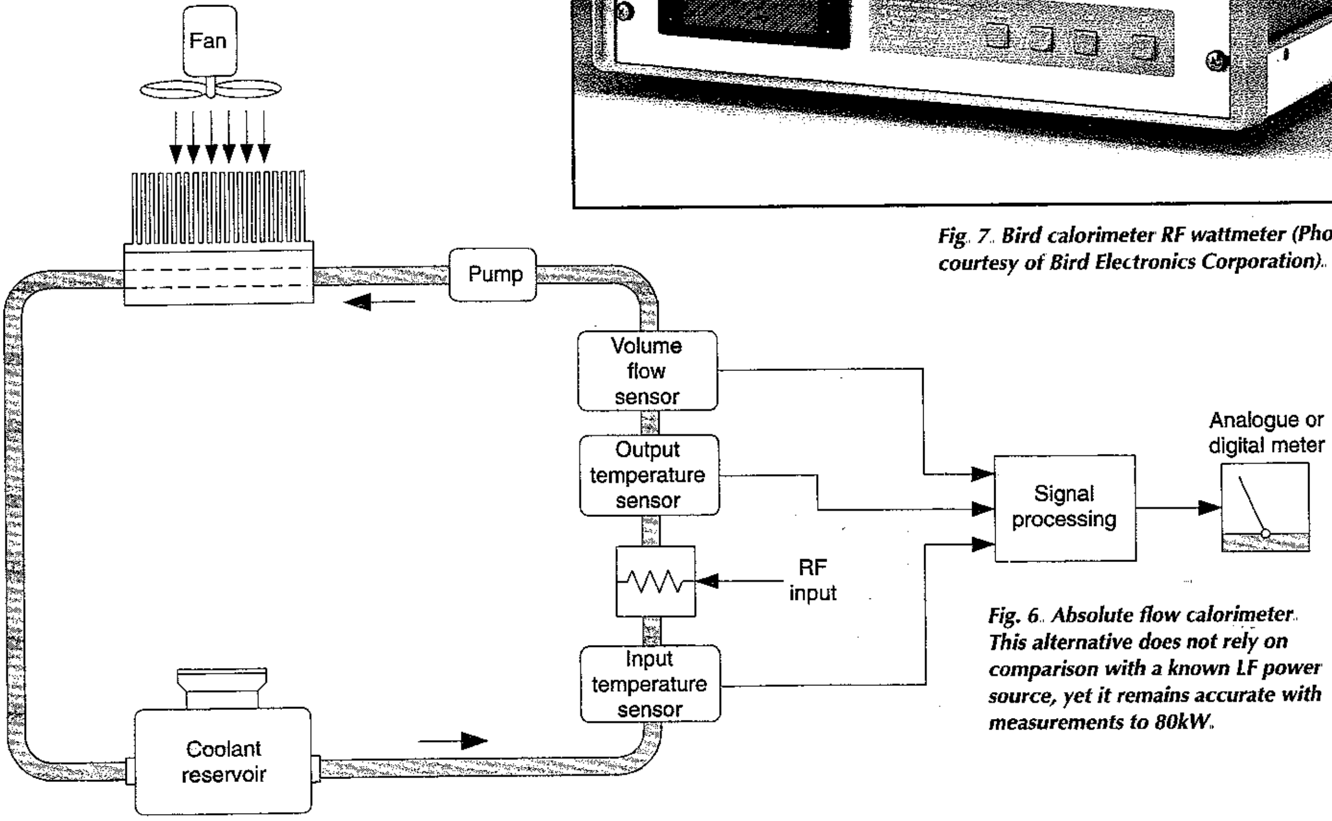


Fig. 6. Absolute flow calorimeter. This alternative does not rely on comparison with a known LF power source, yet it remains accurate with measurements to 80kW.

erator output to zero, and then applies the unknown RF power to the receiver. The S-meter reading is noted; for practical reasons, adjust the attenuator to let the meter fall on a specific indicator marking).

Next, the signal generator output is increased until the S-meter reading goes up one S-unit, which will be either 3dB or 6dB, depending on the design of the receiver. The output level of the signal generator is therefore equal to that of the unknown power source.

Error and uncertainty sources

All measurements have some basic error, i.e. a difference between the actual value of a variable and the value read from a meter. The three dominant classes of error in RF power measurements are mismatch uncertainty, sensor uncertainty and meter uncertainty.

Meter uncertainty is error due to problems in the meter indicating device itself. It might be a measurement error, i.e. a difference between the actual output voltage and the displayed output voltage, which represents power. You might see zero set error, zero carryover, drift, noise and other sources of instrument error.

On analogue meters there are also additional error sources. For example, the width of the pointer covers a certain distance on the scale, so creates a bit of ambiguity. Also, there may be a parallax error if the meter is read at an angle.

Digital meters exhibit quantisation error and last-digit bobble error. The quantisation error comes from the fact that the digital representation of a value can only assume

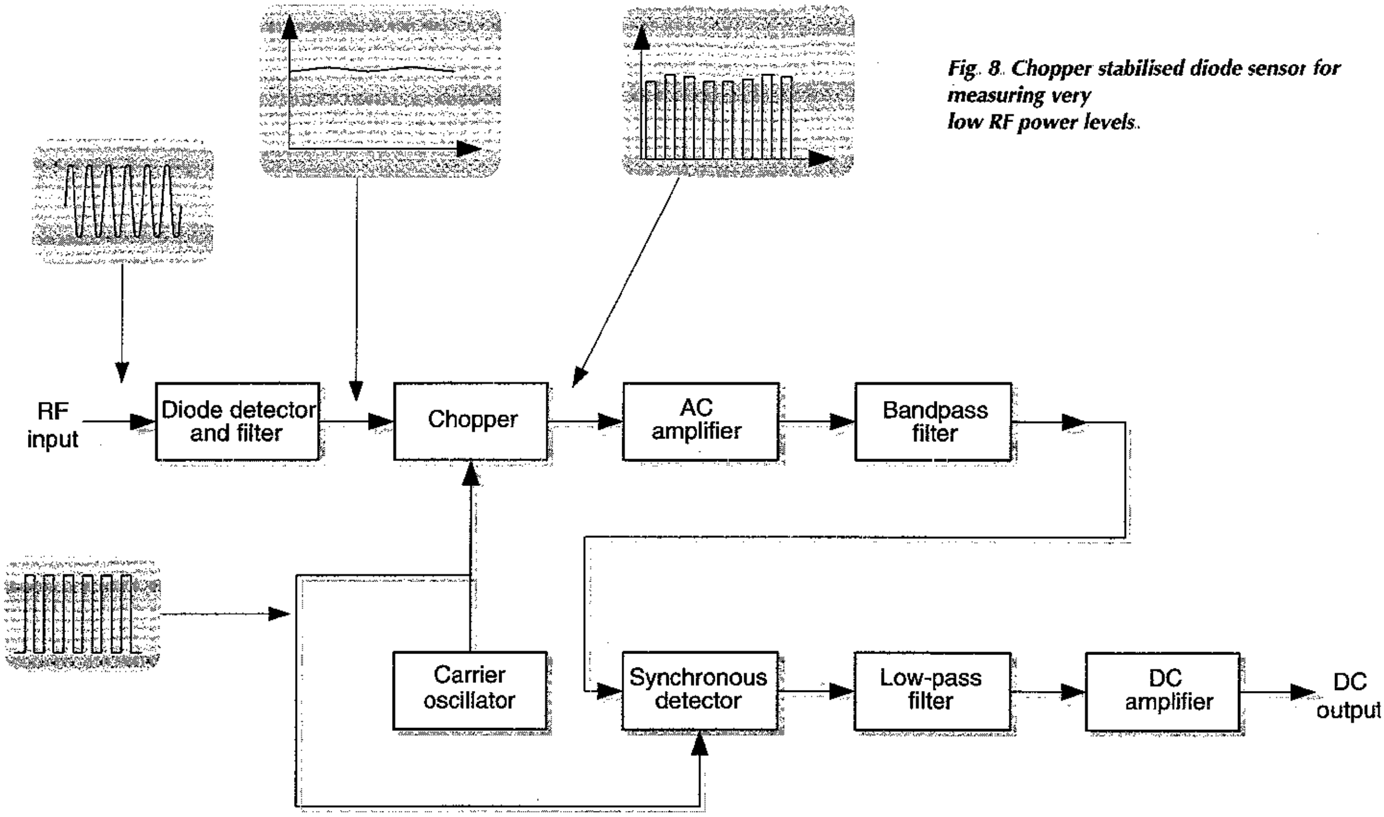
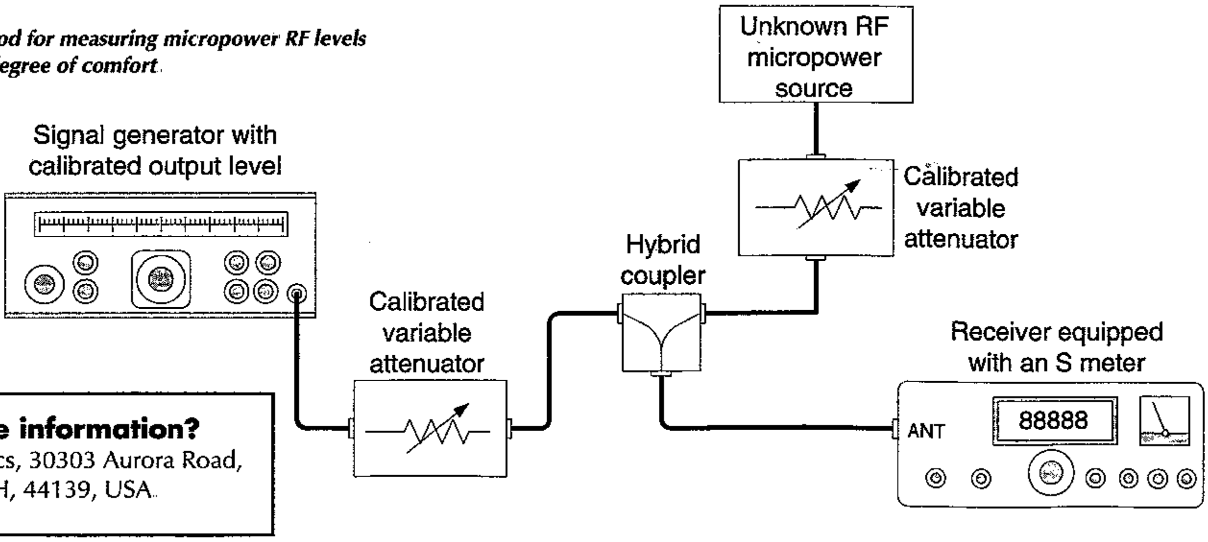


Fig. 8. Chopper stabilised diode sensor for measuring very low RF power levels.

Fig. 9. Method for measuring micropower RF levels with some degree of comfort.



Need more information?
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certain discrete values, and an actual value might be halfway between the two authorised levels. Last digit bobble – a ±1 count error – results from the fact that the least significant digit tends to bounce back and forth between two adjacent values.

Sensor error may come in a variety of guises, depending on the nature of the sensor. Thermistors and thermistors, for example, have different forms of error. Most sensors, though, exhibit an efficiency error due to losses in the sensor. This occurs when some of the applied RF energy is radiated as heat rather than being used to affect the output reading. The manufacturer of the sensor may express this problem as a calibration uncertainty or calibration factor.

Mismatch loss and mismatch uncertainty. The mismatch loss occurs when a voltage standing wave ratio – SWR or VSWR – exists in the system. Maximum power transfer occurs when a source impedance and a load impedance are matched. If these impedances are not matched, then a portion of the power sent from the source to the load is reflected.

The reflection coefficient, ρ, is,

$$\rho = \frac{VSWR - 1}{VSWR + 1} \qquad (10)$$

Table 1. Reflection coefficients for VSWR values from 1:1 to 3:1.

dB(μV)	dBm	Watts	V	μV
7	–100	1.000E–13	2.236E–06	2.24
12	–95	3.162E–13	3.976E–06	3.98
17	–90	1.000E–12	7.071E–06	7.07
22	–85	3.162E–12	1.257E–05	12.57
27	–80	1.000E–11	2.236E–05	22.36
32	–75	3.162E–11	3.976E–05	39.76
37	–70	1.000E–10	7.071E–05	70.71
42	–65	3.162E–10	1.257E–04	125.74
47	–60	1.000E–09	2.236E–04	223.61
52	–55	3.162E–09	3.976E–04	397.64
57	–50	1.000E–08	7.071E–04	707.11
62	–45	3.162E–08	1.257E–03	1 257.43
67	–40	1.000E–07	2.236E–03	2 236.07
72	–35	3.162E–07	3.976E–03	3 976.35
77	–30	1.000E–06	7.071E–03	7 071.07
82	–25	3.162E–06	1.257E–02	12 574.33
87	–20	1.000E–05	2.236E–02	22 360.68
92	–15	3.162E–05	3.976E–02	39 763.54
97	–10	1.000E–04	7.071E–02	70 710.68
102	–5	3.162E–04	1.257E–01	125 743.34
107	0	1.000E–03	2.236E–01	223 606.80
112	5	3.162E–03	3.976E–01	397 635.36
117	10	1.000E–02	7.071E–01	707 106.78
122	15	3.162E–02	1.257E+00	1 257 433.43
127	20	1.000E–01	2.236E+00	2 236 067.98
132	25	3.162E–01	3.976E+00	3 976 353.64
137	30	1.000E+00	7.071E+00	7 071 067.81

Table 1 shows the reflection coefficient for VSWR values from 1:1 to 3:1. Single-ended mismatch loss in decibels is,

$$L_{mismatch} = 10\log\left(1 \pm \rho^2\right) \ \ \text{dB} \qquad (11)$$

If the system is mismatched on both ends, mismatch loss is,

$$L_{mismatch} = 20\log\left[1 \pm \left(\rho_1 \times \rho_2\right)\right] \qquad (12)$$

The mismatch uncertainty, expressed as a percent,

$$L_{uncert.} = \pm 2 \times \rho_1 \times \rho_2 \times 100\% \qquad (13)$$

Assume that there is a 1.75:1 VSWR at the source end, ρ_1=0.27, and a VSWR of 1.15:1, at the sensor/load end, ρ_2=0.07. The mismatch uncertainty is,

$$L_{uncert} = \pm 2 \times 0.27 \times 0.07 \times 100\% = 3.78\% \qquad (14)$$

Total uncertainty. The total uncertainty in the measurement involves the mismatch uncertainty, calibration factor uncertainty and instrumentation uncertainty. If a reference power source is used in a comparison measurement, it also involves power source uncertainty.

There are several ways to state the total uncertainty. Two of these are worst-case uncertainty and root-sum-square uncertainty. The worst-case uncertainty is the sum of all individual uncertainties in the direction that maximises the overall uncertainty. For example, imagine a system with,

Mismatch uncertainty	3.78%
Calibration factor uncertainty	1.76%
Instrumentation uncertainty	0.95%
Power reference uncertainty	1.35%

The worst case uncertainty is their sum:

$$Uncertainty = \pm(3.78\% + 1.76\% + 0.95\% + 1.35\%) = \pm 7.84\%$$

Real errors are rarely worst case, but rather are uncorrelated to each other. The root sum squares, or RSS, method allows a single error term to represent the average errors of the system. For a system with four sources of error, as above, E_1, E_2, E_3, E_4 and E_5, the RSS error is,

$$RSS = \sqrt{E1^2 + E2^2 + E3^2 + E4^2} \qquad (15)$$

In terms of the values above,

$$\begin{aligned} RSS &= \sqrt{3.78\%^2 + 1.76\%^2 + 0.95\%^2 + 1.35\%^2} \\ &= \sqrt{14.29 + 3.1 + 0.9 + 1.82\%} = \sqrt{20.11\%} \\ &= 4.48\% \end{aligned}$$

Compare the worst case error of 7.84% with the RSS error of 4.48%. Expressed in terms of decibels, the RSS percent loss is,

$$RSS(\text{dB}) = 10\log\left[1 \pm \left(\frac{RSS\%}{100}\right)\right] \qquad (16)$$

In summary

This article, and its more background-oriented counterpart that appeared last month, has dealt with the technology of RF power measurement, from very low micropower levels to the multi-kilowatt levels used by broadcasters. ■

Last month, Joe discussed some of the basic methods for measuring RF power, and some of the more common in-line bridge circuits.