RF Output Power vs Load Impedance

By Grant Bingeman, PE, KM5KG

THIS IS AN article based primarily on empirical evidence, and is not the usual theoretical treatment of the subject of PA design, although it is in full agreement with the laws of physics. As such I think you will find it offers some fresh information in the spirit of amateur radio and experimentation, and will be of particular interest to QRP (10 watts SSB, 5 watts CW) aficionados.

SETTING THE SCENE

CONVENTIONAL WISDOM asserts that the RF power output level from a transmitter is optimal when the impedance presented to the power amplifier is closest to its design centre value. An RF output network serves to transform the typical 50Ω load impedance to this desired PA value, but what happens when your antenna presents something other than 50 + j0Ω to your transmitter? Most of us are aware that a transmitter load impedance specification often simply refers to a maximum tolerable VSWR value. Since there are an infinite number of impedances that fall within the typical load VSWR tolerance specification of 2.0, one might ask the question, 'Are some of these impedances better than others?' This article will discuss specifically how much the *measured* PA efficiency and RF power output level from an MFJ 9420 vary over a large set of impedances other than 50Ω resonant, and what this means to your received signal strength. If QRP is defined as 10 watts PEP for SSB operation, it would be good to know if certain loads caused the PA to deliver more than 10 watts. For example, if you are working towards a QRP Worked All States award, but some of your QSLs were made at 11 watts, how would you feel?

The MFJ 9420 is a CW and SSB 'travel radio' rated at 10 watts PEP, tuned to the 20m amateur band. Its PA consists of an MRF477 transistor operating single-ended class AB. This heat-sinked transistor is capable of dissipating 80W, so is not in much danger of burning up in this application, which is probably why the load VSWR spec for this radio is a relatively high 3.0. The output network of the 9420 consists of a 1:4 transformer followed by two 50:50 Ω, -90° pi networks (**Fig 1**). Thus, a 50Ω resistive load presents about 12.5Ω to the PA. Since the phase shift across the output network is 180°, any impedance at the output of the transmitter appears as that same impedance divided by four at the collector of the transistor (impedances repeat every 180° on a lossless transmission line). This is a relatively broad-band output network, and behaves pretty much the same across the entire 20m band from 14.0 to 14.35MHz. By contrast, class C amplifier output networks have a much higher Q and tend to have a narrower bandwidth. Some amateur radio CW transmitters use a class C RF amplifier.

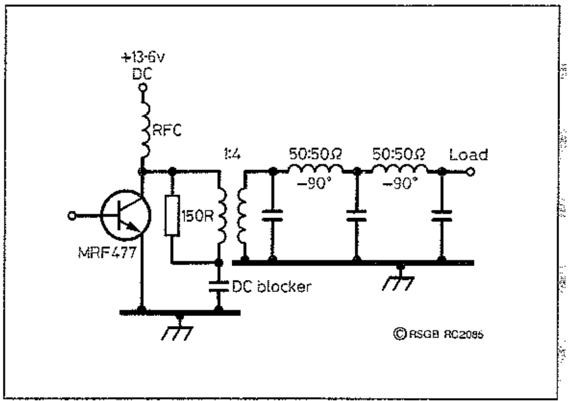

Fig 1: Circuit diagram of the PA stage of the MFJ 9420.

PA TRANSISTOR

USUALLY THERE IS some collector-to-emitter capacitance built into the PA transistor, and if this is greater than that required by the output network, it has to be parallel-resonated with an inductance, or otherwise accounted for in the design. According to the Motorola published data, the MRF477 can be modelled as about 1300pF in parallel with 2.2Ω when delivering 40W at 14.2 MHz, but since the MFJ 9420 PA is operating at only 10 watts PEP nominal, the actual parallel equivalent circuit for this condition is not specified. However, the self inductance of the 1:4 transformer will tend to offset the collector capacitance, so we might assume for the moment that these 'stray' reactances wash each other out, just to keep things simple. Besides, best PA performance may not occur exactly at resonance anyway. There is often a compromise between distortion, power output and efficiency.

The MRF477 is a bipolar NPN silicon transistor, or BJT. If it were a FET, it might tend to behave as a tetrode or current source. Bipolar transistors, on the other hand, are said by some to behave as a triode or voltage source, although they can be modelled as an exponential voltage-controlled current source in Spice analysis. Many models assume that there are no power supply limits, and no feedback, deliberate or stray. However, in the real world, there is not much headroom designed into a transmitter power supply, because unnecessary headroom wastes money. During these tests I used a big power supply that actually cost more than the transmitter under test, but at least I knew its current rating or voltage regulation was not going to taint the results. So keep in mind that you may get different results with an economical power supply, or with a different type of RF power transistor. And RF feedback can very significantly alter the behavior of a PA as the load is varied. In any case the main point of this article is that, rather than relying on theoretical device models, I decided to *measure* the PA performance of my MFJ 9420.

PA DESIGN

THE PA HAS a 150Ω stabilizing or damping resistor directly across the primary of the transformer, which pulls the 12.5Ω down to about 11.5Ω. This means that about 8% of the PA output power is wasted in the damping resistor, and 92% is delivered to the output network. This is a small price to pay for parasitic suppression under variable load conditions. It means that spurious emissions are minimized and PA stability is enhanced, reducing the chances of over-dissipation and failure of the transistor when operating into mismatched loads.

With no load whatsoever attached to the transmitter, I measured a PA DC current of 0.4A when using a 13.6V DC supply. I ran it for 30 seconds with no problems, but would not recommend this as a common practice with other transmitters where the transistor might be running closer to its maximum ratings or where an open-circuit at the output of the transmitter may reflect as a short-circuit at the PA (when overall output network phase shift is near an odd multiple of 90°).

The PA RF choke in the power supply lead has about 0.6Ω of DC resistance. With the key down and 13.6V supplied to the 9420, the RF power delivered to a 47 - j10Ω load is about 9.0W. The stray reactances between the UHF connector and the printed circuit board trans-

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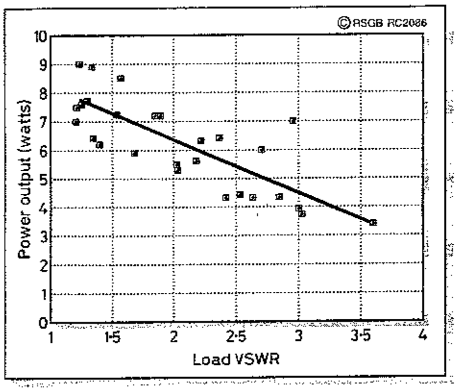

Fig 2: MFJ 9420 power delivered to a mismatched load.

form this to about 48 - j5Ω at the last capacitor in the output network. The DC input current to the radio is about 1.64A under these conditions, of which 0.12A is the quiescent current with the key up, and 0.23A is the current drawn by the oscillator and driver stages. This leaves 1.29A delivered to the PA, which means the voltage drop across the RF choke is about 0.8V, leaving 12.8V across the PA transistor. Thus the transistor input power is 12.8V times 1.29A, or about 16.5W, yielding an efficiency of about 54% at 14.25MHz, which includes output network and damping resistor losses. If you count the loss in the choke, about 1.0W, the overall PA efficiency is a bit lower, about 51%. For the remainder of this article I will include the choke losses in the PA efficiency figures, but 51% is not bad for a practical class AB HF amplifier

The insertion loss of the DC ammeter in series with the PA RF choke was accounted for in the data collection. The voltage drop across this meter was almost small enough to ignore (about 0.2V), but I corrected the results anyway.

Note that the PA bias and all other parameters were left at the factory settings throughout the testing. Using an attic dipole 30ft off the ground, this particular 9420 received excellent SSB signal reports in Italy and Brazil from its Dallas QTH in April 1998, so the factory settings must be OK.

The power delivered to the load was determined by measuring the peak-to-peak value of the RF waveform across the resistive portion of the load with an oscilloscope, dividing this value by 2.82 to convert from peak-to-peak to RMS, squaring the result, then dividing this number by the load resistance:

$$P = (V / 2.82)^2 / R$$

The ground side of the scope probe was always attached to the grounded side of the resistor in the load. The reactive component in the load was floating. The impedances were measured with a Hewlett Packard vector impedance meter calibrated to an NBS standard. The oscilloscope was recently calibrated in an ISO9000 lab, and its accuracy is better than 2%. In terms of measured power, this means that the accuracy was better than about 4%.

The following data (**Table 1**) were taken with a constant 13.6V DC supplied to the transceiver. Note that many 13.8V supplies are not very well regulated, and often the cable between the supply and the transceiver has a significant voltage drop across it as well when the key is down, especially if there is an in-line fuse. When using a portable battery pack, there will also be some sag in the voltage, unless it is a large, fully-charged battery or a good voltage regulator is built into the battery pack. The 9420 uses a number of voltage regulators on its printed circuit cards, but the PA is connected directly to the 13.8V DC input and has no voltage regulation.

The 9420 is designed to operate over a supply voltage range of 12 to 15V DC. There is no series protective diode, only a shunt crowbar diode and a fusible printed circuit trace, so be careful not to hook up your power supply leads backwards! If you add a conventional fuse, you may find that you lose half a watt in its resistance when the key is down.

RESULTS

WE CAN DRAW some general conclusions from these data. First of all, one can see that the general trend per **Fig 2** and **Fig 3** is towards lower power output and efficiency with increasing VSWR. It also appears that for a given VSWR, power output degrades less when the load resistance is lower than the nominal 50Ω. However, PA efficiency and heating are both worse on this low resistance side of the Smith chart (**Fig 4**). I sketched-in some rough constant-power curves on the Smith chart, but more data points would be required to plot these accurately. These curves form concentric rings around the maximum power output location, which is generally at the centre of the Smith chart.

All of the data tend to indicate that the PA is behaving more as a voltage source than a current source, but it is clearly not an ideal voltage source. A very stiff voltage source would produce four times as much power in a 25Ω resistive load, as it produced in a 100Ω load. And at first glance I don't see an obvious constant source impedance value that would account for the measured results either, or that such a linear source impedance even has to exist.

Note that the correlation of PA power dissipation and efficiency with load resistance is true both at the output of this transmitter and right at the PA, since the phase shift across this network is 180° lagging. Therefore you could probably extrapolate this relationship to other transmitters using other output networks, if they used the same type of PA. For example, you would expect the opposite effect to occur in a transmitter having a -90° or -270° output network. That is, a high output load resistance would reflect as a low PA load resistance in such a transmitter, which could result in possible over-heating of the PA. The idea is to translate the load impedance from the output of the transmitter to the PA, keeping in mind that a low PA load resistance is going to stress the PA more than a high load resistance, at least in the MFJ 9420.

By the way, here is a trick question. Which load has a lower VSWR in a 50Ω system: 50 + j40Ω or 70 + j40Ω?

Did you think it was the load with the resistance closest to 50Ω? The correct answer is 70 + j40Ω, which has a VSWR of 2.09, as opposed to 2.18 for the 50 + j40Ω load. Which load is better for your transmitter, assuming you don't have an adjustable impedance matching network between these loads and your PA to compensate for the mismatch? Well, you are probably going to have to measure your transmitter RF power output, input power, intermodulation distortion and spurious RF content to fully answer that question, since all these performance criteria will vary from one transmitter to the next.

You can get a reasonable idea of the power delivered to your load by subtracting the reflected power reading from the forward power reading of your directional coupler. By the way, when was the last time you verified the accuracy of your power meter, or calibrated the impedance of your dummy load? Chances are your reflectometer, or directional-coupler, or magni-phase, or power-meter, or SWR-meter may only provide reasonable accuracy for loads close to 50Ω. I also measured a commercial '50Ω' ham radio load as 56 + j0Ω at 14.25 MHz, so when in doubt, be sure to measure. A commercial dummy load may be specified as having a VSWR of 1.2 over a fixed frequency range, and may never present 50 + j0Ω at any frequency.

ALTERNATIVES

YOU CAN ALSO determine the delivered power to your load as I^2R, assuming you have an accurate RF ammeter and impedance measuring device, or as V^2/R assuming you have an accurate RF voltmeter or oscilloscope. A calorimetric load is used by professional transmitter manufacturers, designers and broadcasters when they want a really accurate measurement of RF power output, and this requires

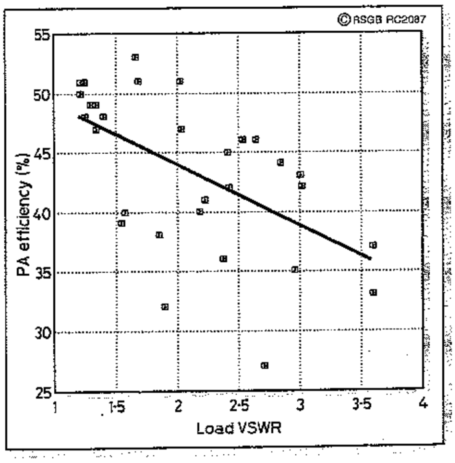

Fig 3: MFJ 9420 PA efficiency vs mismatched load.

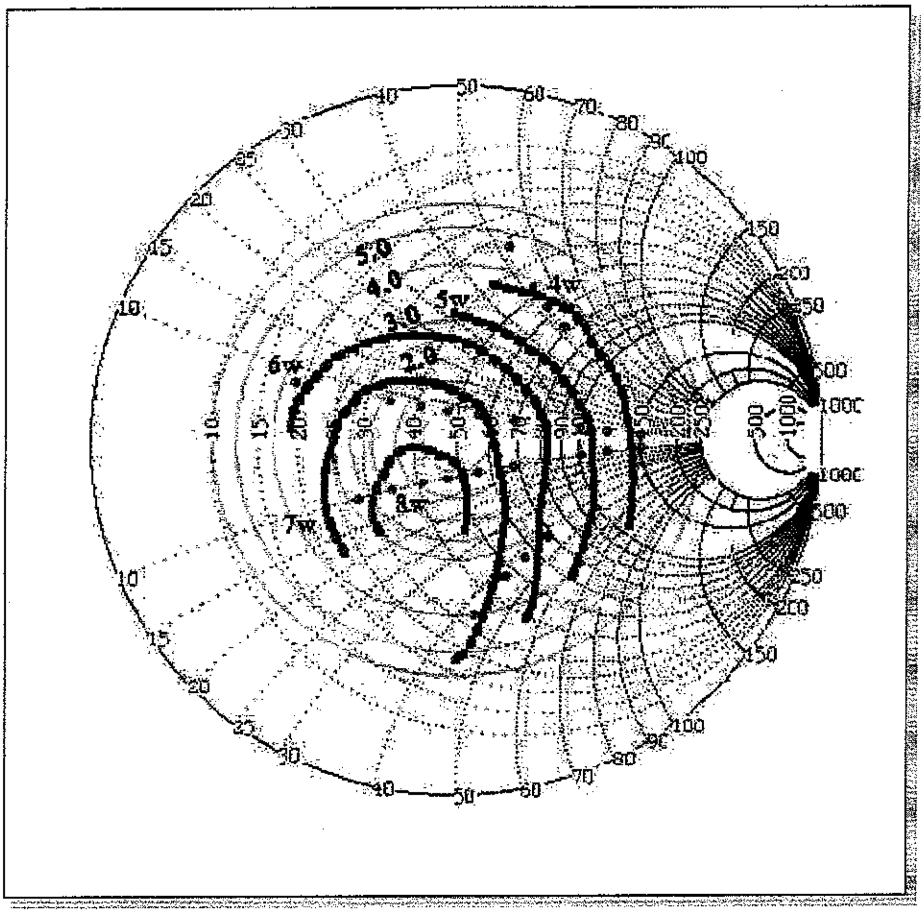

Fig 4: Smith chart showing MFJ 9420 output power against output load.

accurate coolant flow and temperature measurement, not to mention knowledge of the specific gravity of the coolant, or humidity if the coolant is air, etc.

Unprocessed single sideband voice modulation requires less average current from the power supply than tone modulation or typical Morse CW, so the PA may produce higher peak transient power outputs for SSB voice than for CW, unless your power supply is very well regulated. If the power supply voltage regulation is reasonably stiff and its current rating is conservative, the peak envelope power and CW output power may be the same. You can consider the PEP value to be the CW value over one RF cycle at the maximum level of modulation. Normal voice transients don't stick around long enough to cause the typical power supply to sag as much as it will during a key-down situation. Have you ever measured the DC voltage supplied to your PA while the key is down or your modulation density is high? How much does it sag? You might be surprised.

Since the radiated field intensity is proportional to the square-root of the power output from your transmitter, a receiver would hardly see any change in signal strength from a 9420 operating into the full range of loads within a 3.0 VSWR circle on the Smith chart according to Table 1. One S unit is typically considered to be 6dB, and the worst relative field for the 3.0 VSWR circle data in Table 1 is 64 percent or -3.9dB. Therefore, one might conclude that as long as the reduced PA efficiency and stability are tolerable, why worry about matching the load impedance down to the nit? If you are voice modulating, the average modulation depth is relatively light compared to some other modes, and the duty cycle of a normal QSO allows the PA to cool quite a bit between transmissions. Of course, if your chosen mode has a high modulation density and high duty cycle, then you should be more concerned about mismatch. But in the case of the 9420's MRF477 PA, even with the worst-case 3.0 VSWR load you will not be operating near the power dissipation rating of this transistor.

Load impedance	SWR	PA input current	PA input power	Resistor voltage	Load power	PA effic.	Relative field	
19 + j8	2.71	1.65 A	22.4 W	30 Vpp	6.0 W	27 %	82 %	-1.7 dB
28 + j8	1.85	1.41	19.2	40	7.2	38	89	-1.0
34 + j8	1.54	1.35	18.4	44	7.2	39	89	-1.0
41 + j8	1.30	1.16	15.8	50	7.7	49	92	-0.7
47 + j8	1.22	1.09	14.8	53	7.5	51	91	-0.8
56 + j8	1.21	1.03	14.0	56	7.0	50	88	-1.1
68 + j8	1.40	0.95	12.9	58	6.2	48	83	-1.6
82 + j8	1.66	0.84	11.4	63	6.1	53	82	-1.7
100 + j8	2.02	0.79	10.7	66	5.5	51	78	-2.2
120 + j8	2.41	0.72	9.8	65	4.4	45	70	-3.1
150 + j8	3.01	0.67	9.1	68	3.9	43	66	-3.6
28 - j10	1.89	1.65	22.4	40	7.2	32	89	-1.0
34 - j10	1.57	1.55	21.1	48	8.5	40	97	-0.3
41 - j10	1.34	1.33	18.1	54	8.9	49	99	-0.1
47 - j10	1.24	1.29	17.5	58	9.0	51	100	0.0 ref
56 - j10	1.25	1.18	16.0	58	7.6	48	92	-0.7
68 - j10	1.35	1.00	13.6	59	6.4	47	84	-1.5
82 - j10	1.68	0.85	11.6	62	5.9	51	81	-1.8
100 - j10	2.03	0.82	11.2	65	5.3	47	77	-2.3
120 - j10	2.42	0.75	10.2	64	4.3	42	69	-3.2
150 - j10	3.02	0.65	8.8	66	3.7	42	64	-3.9
33 - j43	2.96	1.47	20.0	43	7.0	35	88	-1.1
47 - j43	2.37	1.30	17.7	51	6.4	36	84	-1.5
56 - j43	2.22	1.14	15.5	53	6.3	41	84	-1.5
68 - j43	2.18	1.04	14.1	55	5.6	40	79	-2.0
33 + j53	3.60	0.67	9.1	30	3.4	37	61	-4.3
47 + j53	2.85	0.71	9.7	40	4.3	44	70	-3.1
56 + j53	2.64	0.69	9.4	44	4.3	46	71	-3.0
68 + j53	2.53	0.70	9.5	49	4.4	46	71	-3.0

Table 1: How the output power of the MFJ 9420 varied for a variety of load conditions.

But there are other performance considerations related to load impedance. For example, will the radio be able to modulate cleanly and fully if the power supply is already taxed by poor PA efficiency? If RF audio processing is used, will the feedback sample be degraded by a poor load? Will PA stability be OK without modulation, but degenerate with modulation when a poor load is present? When in doubt, play it safe and match that impedance.

Keep in mind that Class C and D RF power amplifiers behave quite differently from Class AB amplifiers, and every class AB transmitter has a different output network, so be careful that you don't indiscriminately apply the information contained in this article to an amplifier operating with a different amount of bias or a different set of filters and impedance matching networks.

In conclusion it appears that when the VSWR of the load impedance presented to an MFJ 9420 is kept below 3.0, the worst reduction in signal strength one can expect is about 4dB, which is less than one S unit. Some additional good news is that if you define 10W PEP as an official QRP level for SSB, then you will probably never violate this limit by operating a 9420 into a mismatched load. Admittedly, Fig 2 is not a terribly scientific plot of all the possible load impedances, but it does show a general trend to lead one to the conclusion that 10W output is only possible when the load is close to a perfect match and the power supply voltage is near 14V. The maximum RF power output I recorded was 9.0W for a power supply voltage of 13.6V DC and a not quite perfect impedance match. If we assume that 10W is possible with a perfect match at 13.8V, this scales to about 12W at 15.0V, the allowed supply voltage upper limit. If we assume that the accuracy of my measurements in a worse case scenario might be as poor as ±10% of PA power, then it might be possible to violate the 10W QRP limit under certain conditions. If you really want to ensure that you stay below 10W, crank back the supply enough to allow some headroom for the resolution accuracy of your test equipment, just in case it might be reading a bit low.

I invite the reader to make his own set of PA performance measurements for various load conditions, and it would not surprise me if there were certain loads that yielded a PA output power greater than that obtained with the nominal 50Ω resonant condition in other transmitters. Of course, this will depend on the power supply performance, the RF output network, the type of PA transistor(s) and feedback, etc. But I think if you characterize your transmitter's PA performance with an empirical set of data such as I did for my little 9420, then you will know exactly what to expect. And if you are operating QRP or looking for extra points in a contest by staying below a certain power level, it is nice to know under what RF load conditions you might get disqualified! ♦

technical feedback

PSK31: A NEW RADIO TELETYPE MODE

RADCOM, DEC '98 & JAN '99

In addition to the implementations of PSK31 on the DSP kits mentioned in the article in January 1999, a Soundblaster® version has been written by DL9RDZ for the LINUX operating system and G3PLX is writing one for Windows®. PSK31 is also now available for the DSPCOM and EasyDSP multi-mode controllers.

The PSK31 web page has moved to http://aintel.bi.ehu.es/psk31.html where, in addition to all the latest news and software, sound clips of PSK31 signals can be heard.

Peter Martinez, G3PLX

MYSTERIES OF THE IONOSPHERE

RADCOM, JANUARY 1999

It is stated that we are considering radiation from the sun, but further on x-rays and cosmic rays are mentioned. X-rays do come from the sun, but cosmic rays are said to originate from the cosmos.

It was said that the lowest ionospheric layer is the D layer. Technically there is a lower layer, the C layer. Cosmic rays ionise this layer as well as extremely energetic particles from huge flaring sites on the sun.

Gwyn Williams, G4FKH

FACELIFT FOR A 13cm STATION

RADCOM, JANUARY 1999

All DB6NT and DK2DB designs have previously been published in *DUBUS*, which is fully bi-lingual. The designs referred to in the article are also in the *Technik IV* compendium.

Roger Blackwell, G4PMK

RadCom Helplines FOR MEMBERS

● Frank, G3RAM, would like to hear from anyone who completed the **G4WIM 50/70MHz Dual Band Transceiver** project, published in *RadCom*, August 1990. G3RAM, QTHR, tel: 01273 493268.

● Ted, G4EGB, would like to communicate with persons who were stationed **at 2 Base Workshops MELF 11** or **Tel-el-Kebir** garrison, before, during or after the war. He is trying to find out the history of the workshops and garrison. G4EGB, QTHR.

● Barry, G3WAL, wishes to thank the many members who responded to his request for assistance in correcting a fault with the tuning mechanism of his **Eddystone 730/4**. It now behaves impeccably. G3WAL.

● Barrie, G3WWL, appeals on behalf of his local ATC squadron for the circuit diagram of the **Plessey PS112** power supply. All expenses covered. G3WWL, QTHR, tel: 0121 353 8874. E-mail: g3wwl@aol.com

● Paul, G8KDQ, needs to buy or borrow the manual for the **Panasonic KX-P1081** and **KX-P2135** printers. G8KDQ, QTHR, tel: 0181 645 0714.

● Phil, G3SES, is looking for technical information and the circuit diagram of the **Marconi** Instruments Signal Generator **TF995A/4**. All costs reimbursed. G3SES, QTHR, tel: 01244 383954.

● Harold, G0EZW sold a **Trio TS-930S** transceiver on the Bring and Buy at the Leicester Rally (Donington Park). He did not have the manual for it at the time, but has now located it. Would the person who bought the transceiver (he telephoned Harold from Ireland, but didn't leave his name, address or callsign) please get in touch. G0EZW, 97 Nottingham Road, Selston, Nottingham NG16 6BU.

● Wilf, G3SWP, is looking for an **MBA-TOR** software plug-in module to receive RTTY and CW. This was originally made by **ICS Electronics**. G3SWP, QTHR. Tel: 01302 859481.

● Greg, G3III, is looking for information on and the circuit diagram of the type **2300** DC **oscilloscope**, made by **Industrial Electronics** of London SW14. All costs reimbursed. G3III, QTHR. Tel: 01608 662222.

● Keith, G4JVX, would like to hear from anyone who is using (or who has used) antennas manufactured by **Hatley** Antenna Technology. He is interested in the one which, according to Hatley, can be laid across roof tiles. G4JVX, QTHR. Tel: 01909 560308, e-mail keithp@psilink.co.uk

● Les, G8AHE, would like to obtain a copy of the **instructions** and any other useful information on the **Trio 9R-59DS** receiver. Also, original knobs for the RF, AF and BFO controls. G8AHE, QTHR. Tel: 0121 458 2406.

● Andre, GM3VLB, is looking for a sure (and ideally free) method of getting a Trio TS-510 to **Slovakia**. He has been unable to sell the transceiver, and now wishes to **donate** it to a licensed amateur in a country where many can only dream of such a modest way of getting on air. Alternatively, if anyone makes him a sensible offer, he will donate the proceeds to a licensed Slovakian amateur. GM3VLB, QTHR.

Helplines is a free service to members. Requests for help are published in the order they are received. We regret it is not possible to provide an undertaking of when any submitted request will be published.