

Doppler Effect

In radio and other electromagnetic waves

by 'Cathode Ray'

Having studied Doppler effect at some length last month as it concerns sound waves, we might suppose that all we had to do to adapt that treatise to radio (or light) waves was to make V (the speed of the waves in metres per second) 299,792,800 instead of 342. That is certainly what is often implied by people who mention Doppler in connection with radio or light and want to make sure that their less enlightened readers know what they are talking about. And unless we are in the astronomy or space travel business, it is probably fair enough in practice. But in theory at least it is a fallacy. And of course we are not going to be fobbed off with anything like that.

If a gunman, approaching us in his car, were to use us for a bit of target practice, and we took the trouble to measure the speed with which the bullets approached us, we would find that it was equal to their speed as fired from a fixed point, plus the speed of the car in our direction. If however the driver was merely sounding his horn, the speed with which the sound waves reached us would be quite unaffected by the movement, if any, of the car. The higher pitch of sound when its source is moving towards us is due, not to faster sound waves, but to the fact that they are radiated from successively closer positions, so reach us at shorter intervals. However, the speed of the waves does depend on whether there is a wind blowing. The speed of that wind, which is the medium that carries the sound waves, has to be added to or subtracted from their speed in still air to get their net speed relative to the listener. Knowing (1) the wave speed in still air, and (2) its actual speed relative to us, we could find the wind speed very simply as the difference between the two.

If electromagnetic waves, of which radio and light waves are examples, were like sound waves in this respect, then one could (if sufficiently well equipped) measure the speed of the medium that was carrying them. But even before Einstein, experiments designed to do so, and which should have done so, failed completely to show any difference in speed or to reveal the existence of any medium. This surprising result has many times been confirmed since then in much more sophisticated experiments. And so scientists have been obliged to accept as a very remarkable fact that the speed of light in empty space is always the same, even to

observers who are in rapid motion relative to one another. This speed is one of the fundamental constants of the universe, denoted by c and equal to 299,792,800 m/s, as nearly as has been measured.

In material media the speed is less than c ; very little less in the atmosphere, but much less in solids.

Not only is light (or radio) unable to travel faster than c ; nothing can (except of course in Star Trek, but even Mr Spock won't reveal how). For if it is a fact that c in space is unchangeable in any circumstances, it follows that distance, mass and time are not the absolute things that common sense tells us they are, but that measuring rods shrink, masses increase and clocks go slower when they are measured by an observer who is moving relative to them. And when the rate of movement reaches c they go to zero or infinity and things cannot go farther than that.

In view of c being so very much faster even than the sort of speeds we read about in connection with flights to the moon—let alone what we do ourselves on the motorway when pushed for time—we might suppose that the relativistic effects could safely be ignored. At a relative speed of 10,000 km/hour (over 6000 m.p.h.) they amount to only about one part in ten thousand million. But in domestic colour television the voltage used to accelerate the electrons in the picture tube is about 25,000, which on a non-relativity basis would give them a speed of about one third that of light, at which the relativity correction is far from negligible. And on the same basis the voltages used nowadays on overhead power lines would make electrons break the light barrier by exceeding c . However, their gain in mass as predicted by relativity prevents this impossible thing from happening. (It is worth noting that electrons can easily be made to go fast enough to exceed the lower-than- c speed of light in solids and liquids; this breach of the light barrier causes no loud bang but only a silent blue glow called the Cerenkov effect.)

But it is the Doppler effect we are supposed to be studying. The point is that with radio and light waves there is only one speed to be taken into account—the *relative* speed between source and observer—whereas with sound waves the speed of the medium comes into it too. In our numerical example we got slightly different values of

the Doppler change in frequency for the same relative movement of source and observer, depending on which was stationary relative to the air. If radio waves had a medium to carry them, corresponding to the air, then the precise amount of Doppler effect would likewise depend on the source and observer speeds relative to it. No difference amounting even to one thousandth part of what would be expected if there were a medium (aether) has ever been detected in any circumstances, so—no medium.

This complication being absent, we might hope that the calculation of Doppler effect for radio waves would be even simpler than for sound waves. But alas. Owing to the relativistic changes in time and distance with speed the calculation is so complicated that I'm not going to trouble you with it here. It was done by 'Quantum' in *Electronic & Radio Engineer*, Oct. 1957, pp. 371 and 372, if you want to see it. For nearly all practical purposes (mainly radar) the Doppler effect is the same in principle as for sound waves where there is no wind:

$$f' = \frac{f(c+v)}{c} \quad \text{or} \quad f \left(1 + \frac{v}{c} \right)$$

where f is the actual frequency radiated by the source and f' is the frequency as we find it when we and the source are getting nearer at a speed v , reckoned in the same units as c .

Even with supersonic aircraft v/c is a very small fraction. The correction to take account of relativity depends on v^2/c^2 so is very much smaller still and quite negligible in the world of transport. Even v/c is so small at, say, 50 m.p.h. that you might wonder how police radar can detect the difference between f and f' . 50 m.p.h. is only 22.4 m/s, so compared with c is only 1 in 13.4 million. The answer is that f is under control and can be made quite large. For easily portable short-range equipment it would have to be large anyway. Suppose it is 10 GHz (= 10,000 MHz) for example; then 1 in 13.4 million is more than 740 Hz, which is easy to detect, and in fact to measure as the beat note between f and f' .

Now that we are coming down to brass tacks (or even more practical symbols; most tacks actually used seem to be of baser metal) it will be necessary to remember as we are hurrying along a speed-restricted road that the term 'observer' doesn't really

fit us now; we are playing the quite different role known as 'target', and the constabulary are doubling for observer as well as source. So this is rather a different case from any we have considered so far.

The officially operated source generates and radiates short radio waves beamed in our direction. When these strike our car they induce in its metallic structure weak electric currents, just as if it were an untuned receiving aerial. Because the distance between it and the source is more or less rapidly diminishing, the frequency of these currents is very slightly higher than that being radiated, to an extent calculable by the Doppler formula just given. Since any receiving aerial also radiates, our car is also a moving source, radiating waves at this slightly raised frequency. (The whole action of the car in this matter is usually referred to by the one word 'reflects'.) The police, who are the observers, also operate a receiver which detects the reflected waves. And because the distance between secondary source and receiver is diminishing at the same rate there is a second rise in frequency, equal to the first. In other words, the rise in frequency between original source and observer in the reflector mode is twice what it is in the simple source-to-observer modes we considered last month. That makes it easier still to detect and measure. All that is needed is a suitable frequency meter, usually of the pulse-counter type, which can be scaled in m.p.h. of the reflector, such as the one we are driving.

Equipment of this kind was devised during the last world war to detect enemy movements. The ordinary sort of radar that had been used so effectively against air attacks enabled aircraft to be detected and their distances and directions to be ascertained. But in trying to do the same sort of thing for land assaults by tanks etc. it was often difficult or impossible to pick them out from assorted fixed reflectors such as trees and structures. So Doppler radar was invented, which was able to distinguish moving reflectors from stationary ones. The same principle comes in useful, of course, even when targets are clear from 'clutter', for measuring the speeds of aircraft or missiles.

As we have just seen, the frequency of the beat note between the radiated and the Doppler-affected reflected waves is proportional to the speed of the reflector relative to the radiator. The higher the speed, the higher the frequency. But the shorter the time to cover a given distance. So whatever the speed, the total number of beats caused when the reflector moves a given distance is always the same. Each half wavelength the reflector moves towards the radiator introduces one extra cycle into the reflected signal. So if the total number of cycles is counted (instead of their frequency as in measuring the speed of movement) the distance moved can be measured, provided of course that the wavelength is known. Since the frequency f of the transmitter, and therefore the wavelength, can be known to very high accuracy indeed, correspondingly accurate measurements of distance can be made.

An obvious practical requirement for

accuracy is that the number of half-wavelengths in the distance to be measured should be large. So for measuring such things as the dimensions of mechanical parts, or coefficients of expansion, radio frequencies are too low and light beams have to be used. Ordinary light is no good, because it is what we would call a random noise signal. What is needed is a light signal of a definite, accurately known frequency. This is what a laser can provide. So a laser beam, with conversion of the beats (or 'interference fringes') into an electrical difference signal by a suitable photodetector, can be used for making extremely accurate measurements of length.

It seems that what was in effect Doppler radar was discovered before it had been invented as such. Reports were published of mysterious whistles heard by experimenters with short-wave receivers. These differed from the continuous whistles which were beat notes between different sets of oscillations (such as a broadcast carrier wave and the unlawful oscillations set up by over-indulgence in 'reaction' by a listener with one of the regenerative receivers of the period) in being short and rapidly falling in pitch, like the whistles often uttered by starlings. This phenomenon was eventually traced to the varying beat notes between a carrier wave and its Doppler-affected reflections from meteors entering the earth's atmosphere.

Effect on standard frequencies

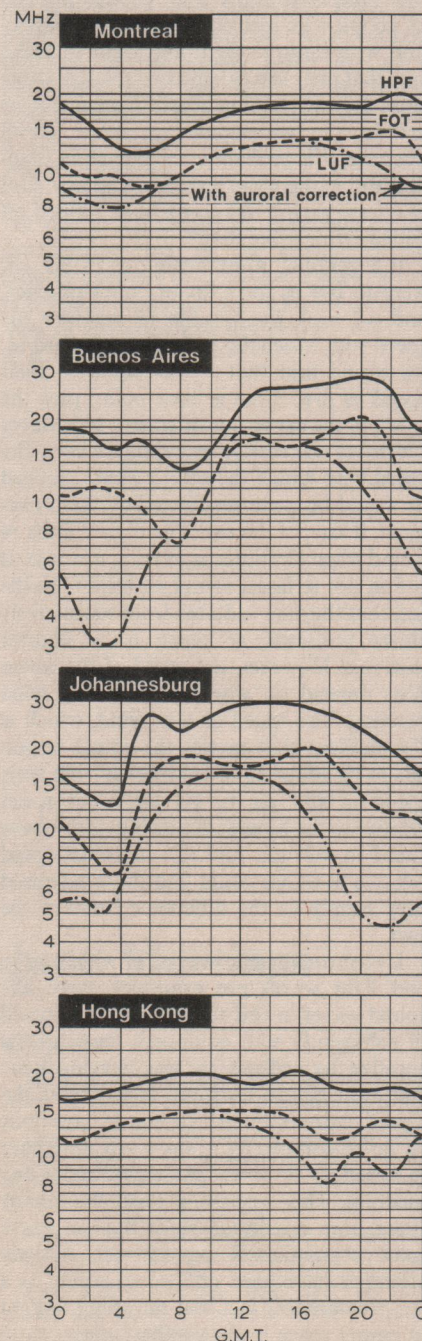
Another naturally occurring Doppler phenomenon is the variation in frequency of signals received from distant standard-frequency transmitters. Their frequencies in the present advanced state of the art are very steady indeed and are actually known to a few parts in ten thousand million. But at long distances they are received as reflections from the layers in the upper atmosphere (ionosphere). As these layers are not rigidly fixed relative to the earth, the received frequency fluctuates and so is reduced in value as a high-grade standard.

Doppler radar is one of the resources used in the exploration of space, and how effective it is for that purpose can be judged from the fact that relative velocity can be measured by it to about 1 mm/s. But simple c.w. radar doesn't indicate range, so pulsed or modulated radar has been devised to provide both kinds of information.

Finally, in connection with optical Doppler effect, which has been used by astronomers since before radar or even radio for measuring the speeds with which the stars are flying away from us, it is interesting to note that sometimes spectral lines are not only shifted towards the red end of the spectrum but are broadened. When this happens it is because the star is rotating around an axis inclined to the straight line between it and earth, making some parts of its surface recede faster than the average and other parts slower. And if all this seems to be outside the scope of *Wireless World*, that isn't necessarily so. The more distant parts of the universe are receding so fast that the Doppler effect shifts some lines right out of the optical frequency band into ours.

H.F. Predictions—June

Observed solar activity so far this year has been consistently around 10% higher than that forecast by smoothed sunspot numbers. In relation to an eleven-year cycle this short-term observation does not merit modification of current predictions. The forecast is of electron content of the ionosphere and this was found to have a high correlation with smoothed sunspot numbers. No direct relation with sunspots has since been established but there are several adaptations of the correlation feature in use today as an ionospheric index which all give adequate results though the necessary smoothing precludes their use for predictions less than three months in advance. On a more practical note the familiar depression of daytime HPFs (highest probable frequencies) during the summer months is most striking on the Hong Kong chart. In all cases LUFs (lowest usable frequencies) are closer to FOTs (optimum traffic frequencies) as a result of this seasonal effect.



Magnetism and Magnetic Units

Understanding the basic relationships, with special reference to SI units

by "Cathode Ray"

The other day I saw—on 'Nationwide', I believe—something about a shopkeeper who persisted in doing business in £sd. (Even he admitted that he wouldn't actually refuse decimal coins. What he thought of paint by the litre and timber by the metre, assuming he was a DIY man, wasn't revealed, probably because his opinion of them wouldn't have been unusual enough to rank as news.)

SI* units, or at least those included in the mksA system, have been with us far longer than decimal coinage. The mks (metre-kilogram-second) system was proposed by Prof. G. Giorgi as long ago as 1901, and although more than 30 years passed before much notice was taken of it, when the break came (as it did in electrical engineering—after the addition of the ampere—more than 20 years ago) the change-over was much faster than the most optimistic had expected. Yet there is still a pocket of resistance that goes on using cgs units though all others have stopped. I mean the people concerned with magnets and magnetism.

Practically everybody uses magnets, in such things as loudspeakers, magnetic pickups and microphones, tape heads and television receivers for example, but not many are so much involved with them as to have to use magnetic units, or, more correctly perhaps, units of magnetism. May be it is because these are a relatively small group, confined largely to Sheffield†, completely single-minded in their devotion to the task of producing ever better magnets, that they are out of touch with the rest of the technological world in this (to them) unimportant matter. Like the Japanese sergeant found in some remote spot in Indonesia, they don't know that the (units) war has been over for 20 years. To be fair, one must admit that there are other possible reasons for this backwardness. It is all very well for the rest of the technological world to be self-righteous about their own acceptance of SI units; their volts and amps and watts and even henries were completely unaffected by the change. In so far as magnetic magni-

tudes have to be considered by some, this was usually a small part of their whole world and the new units could be accepted without too much upheaval. But for specialists in magnetism, cgs units were part of their tradition, and much greater mental adjustment was required. And even now, when challenged they can claim more than mere mental inertia as an excuse: with some justification they can retort that reckoning flux density per square metre is not strikingly appropriate in this day and age of microelectronics. Square centimetres are much nearer the mark, especially in the loudspeaker magnet trade. Their reasonableness in pleading against the inconvenience of having to specify a typical magnet flux as, say, 0.0015 webers may at this point be adulterated by a certain amount of low commercial cunning, since 150,000 maxwells is much better calculated to impress potential customers. Another argument that will undoubtedly be raised is the convenience of the cgs permeability of air being equal to 1, instead of $4\pi/10^7$ as in SI.

So the magnet trade at least may be hard to convince. Perhaps a better line to take with them than extolling the virtues of SI (which they will have difficulty in seeing, even if they want to see them, which is unlikely) is the negative approach—to point out that there is no more future for cgs units than for £sd coinage. Their sons—and daughters—are being brought up on SI, and most fathers don't like to be seen as squares in their own business. And even their hi-fi customers, looking up the current loudspeaker lists as I am just now, may soon be wondering what these gauss and maxwells—and even 'lines'—are. When the magnet men realize they are talking an archaic language to the new generation of big money spenders they will change.

The readers I have in mind are not the members of the magnet trade, nor the young who know only SI, but those who were brought up on cgs and are not yet too handy with SI, together with all who are hazy about magnetic quantities of any kind and their relationships to the familiar amps and volts and ohms.

So first of all I will show how magnetic circuits correspond to electric circuits. I know that this is an extremely unoriginal procedure, found in nearly all the elementary books. I used it myself in the September 1947 issue, but even if you had been born by

then you would hardly remember it. And I know that superior persons, looking for a chance to demonstrate their superiority, will point out that this is a false analogy, since magnetic flux corresponds to electric flux, not current. But practically nobody outside the classroom, and few of those inside it, are really familiar with electric flux and elastance. It is a basic principle of teaching that the obscure should not be explained in terms of the more obscure. So I'm going to liken magnetic flux to electric current, with the warning that there is a more perfect analogy to come later.

I hopefully assume that everyone who is still with us understands Ohm's Law. No; I'm not thinking of the pedantic aspects of it that were my subject in the August 1953 issue and can be seen to this day in "Second Thoughts on Radio Theory". All I mean is the relationship between volts, ohms and amps ($I = E/R$), and how resistance depends on the dimensions and resistivity of the circuit or part of a circuit concerned. So, in Fig. 1, the resistance of the bit of wire is

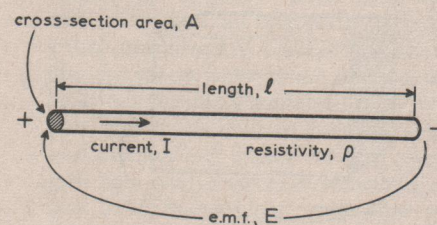


Fig. 1. Ohm's law applied to a piece of wire to find the current flowing through it, given the dimensions and resistivity of the wire and the e.m.f. applied to it.

directly proportional to its length l and to the resistivity ρ of the metal, and inversely proportional to the cross-sectional area A :

$$R = \frac{\rho l}{A} \quad (1)$$

This is true whatever the units of R , l and A . But the value of ρ depends on those units. In SI the basic unit of length is the metre, so ρ is the resistance between two opposite faces of a metre cube of the material, and in the equation l must be in metres and A in square metres, or metres² as we are encouraged to write it. There is nothing to stop

*Système Internationale d'Unités.

†To forestall indignant retorts, or even physical assault, from citizens of Sheffield, I would assure them that I have no wish to bring their city into contempt. By all accounts it is an admirably progressive one, not least in the reduction of atmospheric pollution.

us reckoning A in square millimetres (mm^2) if we prefer, so long as we allow for this deviation by dividing by 10^6 . For ordinary circuit materials ρ is a constant at any one temperature, which is more or less what Ohm was on about. (He didn't know anything about volts, amps, or even ohms.) For metals ρ increases slightly as the temperature rises. For a lot of other things it falls. And for electronic devices it depends mainly on V or I , but of course Ohm knew nothing about them.

One must admit that this resistance formula (1) is not very often used in practice. The resistance of wire is given in tables, and the resistance of resistors is shown by the colour code they bear. If in doubt one can easily measure the resistance with the usual multirange meter. The resistances of electronic devices cannot be calculated by the formula, because ρ is unknown; anyway, one is not usually interested in their resistances as such so much as in the varying relationship between E and I , given by characteristic curves. The main purpose of eqn. 1 is to provide a clear picture of how units of resistance depend on circuit dimensions.

So much for the recapitulation. Now for the analogy. To change over to a magnetic circuit, for electromotive force E volts put magnetomotive force F amps (yes!), for current I amps put magnetic flux Φ webers (Wb), for resistivity ρ put reluctivity ν , and for resistance R ohms put reluctance S amps per weber (A/Wb). (Note: ohms could be called volts/amp, which would make the resemblance of form still closer. Incidentally, in specifying the full-scale current drain of voltmeters, their manufacturers call amps ohms per volt, but in this case the reason is unknown.)

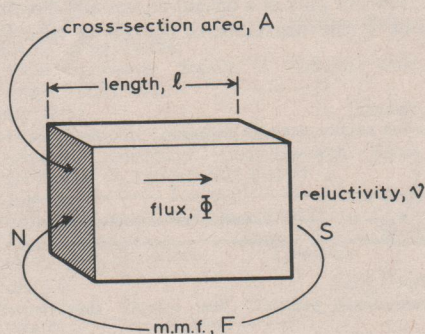


Fig. 2. This is a magnetic analogue of Fig. 1, showing how the magnetic flux in a block of (say) iron can be calculated.

In Fig. 2 we have, say, a piece of iron such as a pole-piece forming part of a magnetic circuit. Following the same reasoning as for Fig. 1 we get

$$S = \frac{\nu l}{A} \quad (2)$$

In both diagrams A has deliberately been made constant throughout the length l to avoid bringing in mathematical complications that would distract attention from the main principle. Although for our theoretical purposes A and l could have been made the same sizes in Fig. 2 as in Fig. 1, in practice magnetic circuits are generally made short

and fat because (1) the object is usually to make Φ as large as possible, and (2) whereas the resistivity of the space surrounding an electric circuit is usually high enough for practically no current to leak into it, reluctivity is never very low so leakage of magnetic flux could be considerable in a long narrow circuit. There is no such thing as a magnetic insulator.

In case anyone is puzzled by reluctivity it might be helpful to reveal that it is the reciprocal of the better known permeability, μ ; i.e., $\nu = 1/\mu$. If you prefer you can put permeability in Fig. 2 and substitute the corresponding quantity conductivity, γ , in Fig. 1. But I thought we might make a bad start if we encountered this rather unfamiliar quantity so soon.

Permeabilities or reluctivities, take your choice, are almost the same for all materials—including empty space—other than those called ferromagnetic, for which μ can be many thousands of times greater and varies enormously according to the degree of magnetization. In fact, such materials correspond very much to electronic devices in electric circuits; characteristic curves are needed, and electronic current and magnetic flux are both limited by saturation.

Before we can tackle magnetic units we have to consider how Φ and F , and other magnetic quantities not shown in Fig. 2, are related to current and voltage. We must make perfectly sure we don't confuse these relationships with the analogy we have just been considering. It would have been better if we could have illuminated magnetic quantities in Fig. 2 by some analogy with totally unrelated quantities, say the flow of tomato chutney along a pipeline on its way to the bottling department; but chutney-motive force is not a sufficiently familiar concept to come within our basic principle of education, and there are other flaws in the analogy. It happens that Ohm's Law is clearer and simpler and better known than any other valid analogy I could call to mind. But now, having I hope got a clear picture of Fig. 2, let us forget about Fig. 1.

We all know that when an electric current flows it sets up a magnetic field around itself (Fig. 3). And that the strength of this field is directionally proportional to the current. Does it depend on anything else? As a one-time famous broadcaster would so rightly have said, it all depends on what you mean by a magnetic field. I've used the term as vaguely as I suspect many people, even some readers of *Wireless World*, think about it. That is exactly why I'm trying to clarify the matter. There are various approaches, but as we have already established a magnetic 'Ohm's Law' let us begin there, without stopping yet to explain exactly what is meant by a magnetic field.

Whatever it is it can be supposed to be caused by what we already know as a magnetomotive force, hereafter to be abbreviated to m.m.f. in line with e.m.f. It in turn is caused by electric current, and depends on nothing else. That is, if you follow the modern practice and count the total current around which the m.m.f. is considered. So if there are 50 wires close together, each carrying 0.1A (usually because the wire is wound into a 50-turn coil) the effective

current is 5A. Formerly one would have said 5 ampere-turns. The main object of SI being to exclude all illogical constants in the relationships between the basic units, the SI unit of m.m.f. has been so chosen that it is numerically equal to the current that creates it. That is why the name of the unit of m.m.f. is the same as that for the basic unit of current—the ampere.

M.m.f. is not directly useful, but only as a cause of magnetic flux; just as e.m.f. is not directly useful for creating magnetism, but only as a means of making the current flow. And just as the amount of current a given e.m.f. will cause to flow in a circuit is decided by the resistance of the circuit, so

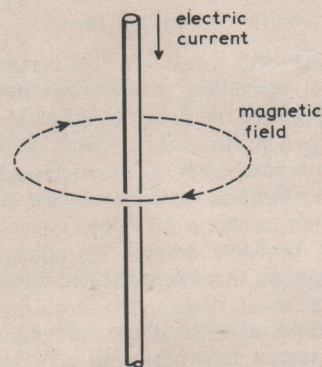


Fig. 3. The basic relationship between an electric current and a resulting magnetic field

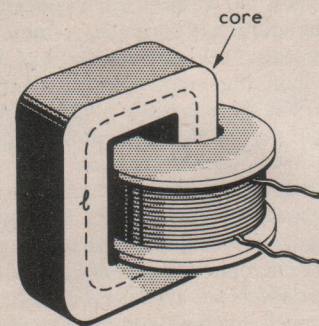


Fig. 4. Here the magnetic circuit linked with a current-carrying coil is assumed (for simplicity) to be confined to a high-permeability core of uniform cross-sectional area A and mean length l .

the amount of flux a given m.m.f. will cause in a magnetic circuit is decided by the reluctance of that circuit. In practice one usually looks at it from the other end: knowing that a certain amount of flux has to be provided, how much m.m.f.—in terms of current and number of turns—is needed?

This can be quite difficult. The shape of a magnetic circuit is usually decided by what it is for. In any case the whole circuit around the current cannot be of the ideal rectangular shape shown in Fig. 2. Assuming that one wants to produce the maximum flux for the minimum m.m.f.—in other words to have as little reluctance as possible—eqn. 2 shows that we would choose one of the special alloys with a very low ν , or high μ . Makers of these alloys supply data showing the values of μ under various conditions. One

of the many forms of core made of such materials is shown in Fig. 4. It is quite possible to make A constant throughout, or nearly so; and although l varies according to distance from the centre an average figure can be used, and so the reluctance of the whole circuit can be calculated reasonably well.

It is seldom as simple as this. Very often, as in electric motors and generators, loud-speakers and moving-coil meters, the flux has to pass through an air gap to be of any use. When the gap is of such a shape that A and l are constant, its reluctance can easily be calculated, μ for air being known very accurately, though one has to allow for edge effects. Because μ for the core is usually so enormous in comparison, the core reluctance can sometimes be neglected, so letting one off the problem of ascertaining it. Another help is to remember that just as resistances in series add up, so do reluctances, and one can split up the magnetic circuit into separate parts, each needing a certain m.m.f. to carry a given flux. (This is analogous to Kirchhoff's voltage law.)

You may be bursting to tell me that most of the magnets in which *Wireless World* readers are likely to be interested are permanent magnets, for which no current is needed. Actually they too require current to cause the required m.m.f., but the molecules of the magnet material itself are so aligned that the electrons circulating in them constitute the necessary current. (In all other materials the alignment is random or in direct opposition, so the magnetic effects of these tiny currents cancel out.) One would have to be rather unusually bright at physics to predict the effective m.m.f., but fortunately the suppliers of permanent magnets also provide all the necessary data. The units used are (or should be) the same as for electromagnets; the theory is too much to push in here and now, and in any case can be understood more easily when we have covered magnetism generally. I may get around to it later, but meanwhile if you can see the March 1961 issue you will find it all there.

If you look up magnet or magnet core data you are likely to find most of it in terms of B and H , with Φ and F and S hardly mentioned, if at all. Even μ may not be specified directly, although it seems to be the most important factor in reluctance. To understand these omissions, let us take a look at a curve of Φ against F for some magnetic material such as iron (Fig. 5). The slope of this curve will be Φ/F . Our magnetic 'Ohm's Law' is

$$\Phi = \frac{F}{S} = \frac{F\mu A}{l}$$

$$\text{So } \frac{\Phi}{F} = \frac{\mu A}{l} \quad (3)$$

The dimensions of the piece of iron, A and l , being fixed, we see that the slope is proportional to μ . To find the actual value of μ we would have to multiply the slope by l and divide by A . This way of presenting the data is silly, because we are not interested in the figures for the piece of iron that the manufacturer's lab people happened to use for their tests, but in the properties of that par-

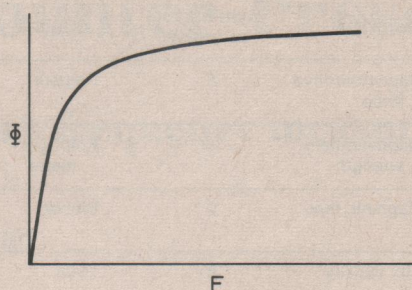


Fig. 5. A graph of flux against m.m.f. for a ferromagnetic material would apply to only one particular size and shape. But by suitable choice of scales of flux density against magnetic field strength the same graph is made to apply to that material in any size and shape.

ticular material, which we can then use to tell us about a piece of the size and shape we might want to use. One way would be to measure a unit cube of the material, so that l and A were both $=1$. But this would restrict the method of measurement very inconveniently, especially with SI units, for a metre cube of iron weighs about 8 tons.

A better idea is to have units that will refer to unit dimensions of the material. So instead of Φ , the total flux, we use the flux passing through unit cross-sectional area: the flux density, denoted by B , in Wb/m^2 , called teslas (T); and what is called magnetizing force or magnetic field strength, H , in A/m . Rearranging eqn. 3 we get

$$\frac{\Phi}{A} \cdot \frac{l}{F} = \mu$$

$$\text{So } \mu = \frac{B}{H} \text{ or } B = \mu H$$

For the reason just explained I didn't bother to provide Fig. 5 with scales, but if B is written in place of Φ and H in place of F then numerical scales would apply to that material in general, regardless of size or shape. (There are exceptions, called anisotropic materials, 'anisotropic' meaning that their properties are not the same in all directions, like wood having different properties along and across the grain.)

Sometimes one comes across data curves showing μ directly in terms of H or B . From the typical B/H curve shape in Fig. 5 we can see that the permeability ($=$ slope) begins high and continues so over a range, beyond which it falls off rapidly towards a certain flux density, called saturation, which is not much more than for air. Under these conditions there would be a lot of leakage flux outside the iron.

Since most magnetic data and calculations are in terms of B and H , referring back to Fig. 1 we may wonder why the same policy is not adopted there, replacing current by current density and e.m.f. by electric field strength. Well, if I had started from the more strictly appropriate analogy, comparing magnetic fields with electric fields, that is just what one would do. Because one is interested in electric fields mainly in non-conducting spaces (inside a cathode-ray tube, for example) current is replaced by electric flux, which is treated like magnetic

flux and reduced to flux density or displacement. For an overall grasp of electric and magnetic theory it is very helpful to consider this analogy in detail, but I assumed that from a more practical standpoint most people are familiar with electric circuits and would like to be clearer about magnetic circuits and fields.

While we are on about fields we might look again at Fig. 3. If the current flowing through the wire (or group of wires) is called I , we now know that the m.m.f. F encircling the wire—at any distance from it—is equal to I , both I and F being reckoned in amps. But because the path length around—call it l again—is proportional to the distance r from the axis of the wire, being in fact equal to $2\pi r$, the m.m.f. is spread over a greater circular length as the distance from the current is increased. So the magnetic field strength

$$H = \frac{F}{l} = \frac{I}{2\pi r}$$

In words, it is inversely proportional to the distance from the current that causes it. We are assuming—in case you didn't know—that the whole of the space around the wire has the same permeability and contains no currents or magnets to upset the cylindrical distribution of field around the wire.

If your information on magnetism was obtained some time ago you may have been wondering why I've about come to the end of this exposition without having ever mentioned 'unit magnetic pole'. Most of the books used to base their treatment of magnetism on it. The more honest of them admitted that no such things exist, which is why I've ignored them. It is rather different with the analogous electrical concept, unit electric charge at a point, because electrons and protons are as near as you like mobile point charges. Another item that has been perhaps conspicuous here by its absence is the 'line of magnetic force', so much used in 'explaining' magnetic fields. They don't exist either, and can be actually misleading if they are allowed to convey the impression that the spaces between are any less magnetic than the lines themselves. But, like the lines cartoonists draw radiating from persons experiencing intense emotion, they at least help one to visualize something that does exist. In particular, they show on a diagram the directions along which a magnetic field acts; for example, in Fig. 3, in circular paths around the current. If there were such things as mobile magnetic poles of negligible size, these are the paths along which they would be moved.

No; I haven't forgotten that I set out to enlighten any who are still groping in cgs twilight. The fact that cgs units don't fit in with the familiar electrical units such as volts and amps has already been mentioned as one of their disadvantages. Another is the fact that there are two cgs systems of units, one based on unit electric charge and the other on unit magnetic pole, and their units differ from one another and from the practical units by factors usually of many millions. Another snag is that unit charge and unit pole were each said to give rise to a flux of 4π units. The reason for this apparently odd choice was that unit flux density

was defined to exist at unit distance from the unit point source of flux. The surface area of the sphere of unit radius is 4π units, so if the flux emerging through unit area of the surface is 1 the total flux must be 4π . By starting on this basis, the originators of the cgs systems eliminated the factor 4π precisely where one ought to find it—in a situation of spherical geometry. The result was that the factor 4π , expelled from where it rightly belonged, broke out in places where its presence could not be justified by the geometry; for example, in the formula for a parallel-plate capacitor.

And in the relationship between current and m.m.f. My electrical engineering tutor, whenever a student was stuck at a problem, sat down opposite him, scribbled on a sheet of paper with a circular motion to represent a current-carrying coil; then repeatedly smiting its interior with the point of the pencil to represent end views of lines of force, hissed 'Magnetomotive force is point four pi times the current enclosed!' This relationship took into account the irrational 4π and the fact that the electromagnetic cgs unit of current was 10A. Nowadays even the densest student should be able to retain the SI relationship 'Magnetomotive force is equal to the current enclosed' without having to be constantly reminded of it.

Fig. 4 shows that interrelated current and magnetic flux are like adjacent links of a chain. We have considered how current in the coil causes an m.m.f. linking the current path. Faraday's greatest discovery was that a change in magnetic flux causes an e.m.f. linking the flux path. The electromagnetic unit of e.m.f. was quite logically defined as that induced when interlinked flux was changing at unit rate (1 maxwell) per second. But unfortunately this turned out to be $1/10^8$ V, or 0.01μ V, which is small even by circuit noise standards. The electrostatic cgs unit of e.m.f., by contrast, is about 300V, because the ratio between the units of e.m.f. in the two systems is equal to the speed of light in centimetres per second. To the uninitiated this might seem as irrelevant as the diameter of the earth or the price of beer. The connection lies in the fact that in both cgs systems the permeability and permittivity of empty space (μ_0 and ϵ_0) are both fixed as 1. Now one just can't have it both ways like this. The reason is that the speed of light (c) is equal to $1/\sqrt{\mu\epsilon}$ for the medium in which it is travelling, so in space is $1/\sqrt{\mu_0\epsilon_0}$. The only way to make μ_0 and ϵ_0 both 1 is to choose units of length and time such that $c = 1$. If the second is retained as the unit of time, then the unit of length must be 299,792,800 metres. Anyone who proposed this as the standard would have no political future.

The inevitable result of making unit length 1cm at the same time as $\mu_0 = \epsilon_0 = 1$ was the emergence of two cgs systems, depending on whether μ_0 or ϵ_0 was chosen as basic, in which units of the same quantities differed by factors of c or c^2 . And the real values of μ_0 and ϵ_0 , which actually are related to c , had to be hidden away in the sizes of the various units. So most of them are wildly impractical. The emcgs unit of resistance, for example, is 0.001 microhm,

Quantity	Symbol for quantity	Unit	Abbrevn. for unit		emcgs equivt.
Magnetomotive force	F	Ampere	A	In practice, the ampere-turn	0.4π gilberts.
Magnetic field strength	H	Amp. per metre	A/m	$= F/l$	$4\pi 10^{-3}$ oersteds
Magnetic flux	Φ	Weber	Wb	$= AB$	10^8 maxwells
Flux density	B	Tesla	T	$= \mu H$	10^4 gauss
Permeability	μ	Henry per metre	H/m	$= B/H$	$10^7/4\pi$ greater
Permeability of space	μ_0	Henry per metre	H/m	$= 4\pi 10^{-7}$	ditto (=1)

while the escgs unit is about a million megohms. SI works on a different principle. By changing over to the metre and kilogram for length and mass, and using the ampere as the unit of current, all the 'practical' electrical units became parts of it, and new magnetic units emerged from them on the same principles. And so the SI unit of m.m.f. is equal to the current enclosed instead of 0.4π times it. And when the magnetic flux is changing at unit rate per second the e.m.f. induced along a linked path is 1 volt.

Does this mean that π no longer appears in electromagnetic equations? Not at all; it means it appears where it logically ought to—as 2π in cylindrical geometry and 4π in spherical geometry, but not in rectangular geometry. The cgs systems were as confusing as a system of measures would be in which the unit of length was such as to make the surface area of a sphere one unit of length-squared.

Of course there is always a snag. Instead of the convenient values of 1 for space permeability and permittivity we have $4\pi/10^7$ and approximately $1/(36\pi \times 10^9)$ respectively. So π and large powers of 10 get back in by the rear entrance! However, it is easier to remember these two values than to have to remember the correct constants for innumerable formulae. If dirt has to be swept under carpets, it is better to have it swept under two already dirty ones if we can rely on there being none anywhere else. There is even something to be said for μ_0 and ϵ_0 not being 1. When they were, students were often led to suppose that H and B were more or less the same thing and μ just a multiplier to take account of the properties of magnetic materials. Then they got into difficulties with the dimensions of equations.

What, then, are the dimensions of μ and ϵ ? The best clue to ϵ is the way the capacitance between two parallel plates is calculated. It is proportional to A , the area of the space between the plates, and to ϵ , the permittivity of whatever occupies that space. And it is inversely proportional to l , the (uniform) distance between the plates. (Edge effects are neglected, or counteracted in some way.) So in any regular system of units

$$C = \frac{A\epsilon}{l}$$

$$\epsilon = \frac{Cl}{A}$$

Therefore

In SI units, C is in farads, l in metres and A in metres². So ϵ is farads \times metres \div metres², or farads per metre. Going back to the electrical circuit analogy, we would find in the same way that conductivity (γ) was in siemens (formerly mhos) per metre, and $1/\gamma$ (= resistivity, ρ) was ohm-metres. An alternative that used to be used was ohms per metre cube, and similarly for the other things; but this looks as if it restricted the measurement to a piece of a particular shape and size of the material tested.

As the analogue for capacitance is inductance we start to get at μ from there. The inductance (L) of a coil—say the one in Fig. 4—is equal to the flux linked with it when unit current flows through it. If we neglect flux in the surrounding air, and use eqn. 3 we have, when F is one unit and Φ is therefore equal to L ,

$$\mu = \frac{Ll}{A}$$

So μ is in henries per metre.

To sum up, here is a table of the SI magnetic units:

PUBLICATION DATE

We regret it has not yet been possible for us to get back to publishing on the third Monday of the preceding month. The February issue will not, therefore, appear until February 2nd.

Ohms per volt

A question of voltmeter manufacture

by "Cathode Ray"

Having to keep up an appearance of infallibility is one of the stresses of youth that cause many to die young. But those that escape it, or with maturity learn better, enjoy not adding loss of face to the discomforts of old age. Thus, instead of being upset by receiving a letter from Mr A. J. Sargent pointing out a slip in my treatise on magnetism in the January 1973 issue I was happy to see in it an excuse for further chat.

The said slip had nothing to do with magnetism, so would not have occurred if I'd stuck to the point. It was a slightly faulty buzz from a particularly energetic bee escaping from my well-stocked bonnet. Its motive force was the practice of voltmeter makers of specifying the current load of their products in ohms per volt. My correspondent pointed out to me that it was the reciprocal of current that was so specified. He tactfully refrained from adding "Fancy Cathode Ray forgetting Ohm's Law!"

Well of course he was perfectly right, and although I doubt if anyone was misled by my error, and it was only the generally accepted kind of sloppiness of speech we use in reckoning petrol consumption in miles per gallon, I really ought always to practise what I preach and use my words carefully.

This particular side swipe comes out at the slightest pretext (such as an article on magnetism) because I hope some day to provoke a voltmeter maker into explaining why he specifies the current load of his meters not only reciprocally but also clumsily in ohms per volt. One doesn't ask for a 13 volts-per-ohm plug, suitable for a 240 amp-watts power supply.

It is in fact an even clumsier practice than at first appears, for in full it has to read "ohms per volt of full-scale reading". So if you want to know how much current is leaking away through your 20,000 ohms per volt voltmeter (to impress you the makers always say 20,000 Ω , not 20k Ω) when it is reading, say, 195V on the 300-V range, you have to divide 195 by 300 times 20,000; and if you concentrate on it sufficiently you get 32.5 μ A as the answer. Personally I think it would be a lot easier if below the voltage scales there was a voltmeter leakage (or load) scale, 0 to 50 μ A, in grey to be distinct from the volt scales and less conspicuous, but there whenever you wanted it. The deflection that indicated the voltage would at the same time show the voltmeter current.

If you did want to know the voltmeter

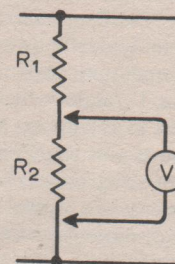
resistance on any range you would simply divide that range (in volts) by the 50 μ A or whatever full-scale current was shown on that particular instrument. In our example, on the 300-V range it would be 300/50, which (as the current is in μ A) is 6M Ω .

Most voltmeters use the same current on all ranges, hence the simplicity of specifying that figure. As for the exceptions that are complicated by more than one full-scale current, note that equally they have more than one ohms-per-volt of full-scale voltage. I'm still waiting to hear why the makers prefer to work in the latter involved terms. M. G. Scroggie, who is very much at one with me in such matters, has been waiting at least 12 years, since the question was first put bluntly in *Radio & Electronic Laboratory Handbook*, 7th edition, and again in the 8th.

What we really want to know, of course, is neither the current nor the resistance. We want to know the voltage between A and B before we connected the voltmeter to those two points. Being very accommodating we would settle for the drop in voltage due to the connecting; it is easy enough to add this to the indicated voltage to give the true reading (subject of course to the possible meter error; and if you haven't studied the relevant British Standard, BS 89, you'd be surprised to see how large that could be. For example, if the reading at 0°C on a portable multi-range moving-coil instrument with a 3in scale was 30V on the 100-V range, the true reading within the tolerances allowed in the Industrial Grade—previously called British Standard First Grade—could be anything from 24.75 and 35.25V. So there would be no sense in logging it to several places of decimals!).

Unfortunately the load error, which is extra, depends on the impedance of the circuit to which the voltmeter is connected. If that is hundreds of times less than the voltmeter resistance then you have little to worry about. But we rarely know what it is, and (especially in circuits subject to feedback) may not even be able to make a reliable guess at the order of magnitude.

One particular but often occurring case is the potential divider (see Figure). Let's suppose it is connected across a relatively low-resistance d.c. source. That puts R_1 and R_2 practically in parallel, so far as the resistance in series with the voltage source and the voltmeter V is concerned. If you have any hesitation about accepting that state-



Current load with a potential divider.

ment, study of the theorem ascribed to Thévenin (by the French) and Helmholtz (by the Germans) is indicated. Note that this effective source resistance is the same regardless of whether one is measuring the voltage across R_1 and R_2 . It is equal to $R_1 R_2 / (R_1 + R_2)$. Call it R_s . The drop in voltage in it due to V is of course $I_v R_s$, where I_v is the current taken by the voltmeter, read off the scale which the voltmeter manufacturing industry will be rushing to insert when it has finished reading this article. (Oh yes?) So we just add $I_v R_s$ to the voltage reading.

If we haven't a clue what the source resistance is, or alternatively have but can't be bothered to perform the above simple calculation or tap it out on the pocket computer, we can get a correction by shunting V by a resistance equal to the resistance of V. Doing this will reduce the reading. This drop is the correction we should add to the first reading. If it is more than about 10% then the correction itself is appreciably inaccurate and we should get a higher-resistance voltmeter.

The late Bainbridge-Bell described a method in which a multi-range voltmeter itself is used to provide an alternative resistance. A reading is obtained on two ranges, the ratio of the higher voltmeter resistance to the lower being m . In most instruments it is the same as the ratio of full-scale readings. Then if V_1 and V_2 are the readings on the upper and lower ranges respectively, the corrected voltage is

$$\frac{(m-1)V_1 V_2}{mV_2 - V_1}$$

A disadvantage of this method is that readings which come low on the scale are less accurate. Both these altered-resistance

methods rely on the circuit as a whole being ohmic (i.e., linear) so may not work well in electronic circuits. In transistor circuits it may be helpful to remember that the base-to-emitter voltage is fairly constant at about 0.55–0.6V for silicon and 0.16–0.2V for germanium.

These methods of correction can be used for a.v. provided also that the a.v. voltmeter is not used on a non-linear part of its range (most of them include a rectifier). And if the circuit is reactive the correction is likely to be very inaccurate. Remember too that a.v. voltmeters are in general less accurate than d.v.

Another curious thing about the habits of meter makers is that although their most popular products measure current as well as voltage (for which they specify voltmeter ohms per volt of full-scale reading) rarely if ever do they act logically by specifying the ammeter in siemens per ampere of full-scale reading. Again, I wonder why, and hope an answer may be forthcoming. Now that the voltages in most electronic circuits are so much lower than they used to be, the voltage lost in the meter when measuring current is correspondingly more significant and ought to be allowed for, or at least allowable for by those who want to do so. But the information is not given. Of course the S/A of f.s.r. form of supplying it is logical only in the context of the illogical Ω/V of f.s.r. which I've been busy deploring. The sensible way would be to have an unobtrusive voltage-drop scale for use when reading current.

I have no doubt that if any instrument makers are taking a blind bit of notice of my constructive criticisms they will be already asking their dictating machines to take a letter pointing out that there are already too many scales to have to find room for on their multi-range test meters, and adopting my suggestions would only make confusion worse confounded. (I don't think on second thoughts they would phrase it just like that.) Perhaps so, but now that a branch of industrial endeavour dignified by the name of ergonomics has been introduced why not use it? If however even this resource fails, at least may we have the full-scale voltmeter current and ammeter voltage included in the specifications in place of the ohms-per-volt rubbish?

MARCH 1974 ISSUE

The issue number on the spine of the March 1974 issue was incorrectly printed as 1461. It should have been 1459, as correctly printed on the contents page. We apologize to readers, librarians and others to whom this error may have caused inconvenience.

Literature Received

PASSIVE DEVICES

Advance Filmcap have sent us a copy of their new capacitor data book, which gives full information on ranges of polycarbonate, polyester, a.c. types, electrolytics and film types of capacitor. Advance Filmcap Ltd, Rhosymedre, Wrexham, Denbighshire WW401

Erie have sent us a wall-chart which covers capacitance ranges and working voltages of their ceramic, electrolytic, paper and film capacitors, together with outline drawings. Erie Electronics Ltd, South Denes, Gt. Yarmouth, Norfolk WW402

EQUIPMENT

A short-form catalogue describing a range of pulse generators, word generators, a.f. oscillators and distortion meters has been published by Lyons Instruments Ltd, Hoddesdon, Herts WW403

Two new product ranges are described in a supplement to the Radiatron short-form catalogue. The Electromatic range of timing, sensing and control modules with relay output is listed and there is a description of the Hopt electromechanical and electronic counters. Radiatron Components Ltd, 76 Crown Road, Twickenham, Middlesex WW404

Constant-potential battery chargers are the subject of a leaflet from Erskine Systems Ltd, Newby, Scarborough, Yorkshire, YO12 6UE. Chargers of capacity from 24V, 3A to 220V, 15A are described in both chassis and cubicle forms WW405

Two low-noise microwave sources are fully described in leaflets from Microwave Associates. The ML13000 series, on Bulletin L/0013, provides signals in the range 1.25GHz to 17GHz, while Bulletin L/0009 details the performance of the ML12000 multi-channel series, working between 1.7 and 10.3GHz. Microwave Associates Ltd, Dunstable, Bedfordshire LU5 4SX WW406

Intended principally as an IEA promotional leaflet, a publication by Feedback, "Teaching Technology", forms a short-form catalogue of a range of equipment for the teaching of electrical, mechanical and control technology. Feedback Instruments Ltd, Park Road, Crowborough, Sussex WW407

Moore Reed have sent us a leaflet on their VT111 "Intelligent" video display terminal, which is field-programmable, containing a central processing unit and a 4k memory. Moore Reed & Co Ltd, Walworth Industrial Estate, Andover, Hants WW408

We have received a leaflet describing a range of kilovoltmeters measuring up to 200kV or more from Hipotronics Inc, Brewster, NY, USA WW409

Bulletins 7602 and 7603 describe a series of Gunn oscillators intended for use as local oscillators in remodulation-type link equipment receivers, between 5.855GHz and 13.27GHz at 3W nominal. Microwave Associates Inc, Burlington, Mass., USA WW410

Data sheets are now available on the Mini 400 series of bench power supplies by Weir Instrumentation Ltd, Durban Road, Bognor Regis, Sussex .. WW411

We have received from Bradley a wall-chart which, in addition to brief information on their range of measuring instruments and microwave sources, contains some interesting general information in the form of conversion tables, pulse parameters, Fourier analysis and the like. G. & E. Bradley Ltd, Electral House, Neasden Lane, London NW10 1RR WW412

APPLICATIONS

We have received from Nordmende a booklet, in English and German, intended to assist technicians in the servicing of digitally-controlled TV receivers by Nordmende. The booklet is a very simple introduction to basic logic circuitry in addition to the television information on the Telecontrol II system. Norddeutsche Mende Rundfunk KG, Zentralkundendienst, 28 Bremen, Postfach 44 85 08, Germany WW413

Mullard have reprinted an article, originally in *Mullard Technical Communications*, entitled "Cleaning Processes for Mullard Resistors and Capacitors on Printed-wiring Boards", which deals with the use of various types of cleaning agent and their effect on component materials. Ref. TP1448, Instrumentation and Control Electronics Division, Mullard Ltd, Mullard House, Torrington Place, London WC1E 7HD WW414

Equipment designed by the BBC Designs Department is often described on information sheets for the benefit of manufacturers who may wish to exploit the designs commercially. We have recently received EP14/1, CO8/501 and RLE, describing a.f. test equipment, 8-bit a-to-d, and d-to-a converters and radio link equipment. BBC Designs Department Liaison Unit, BBC, London W1A 1AA WW415

GENERAL CATALOGUES

A catalogue of liquid-tight fittings, strain-relief terminations, Ty-rap harnessing, connectors, tools and wire-markers, has been produced by Thomas and Betts Ltd, Greenhill House, 90/93 Cowcross Street, London EC1M 6JR WW416

The 1974 index and price list from ECS is now available, covering products from RCA, SGS-Ates, IR, Keyswitch, AEG/Telefunken, Emihus, Seatronics, Allen Bradley, Guest International, Semitron and Litesold. ECS (Windsor) Ltd, Thomas Avenue, Windsor, Berks. WW417

MISCELLANEOUS

The Final Acts of the World Administrative Telegraph & Telephone Conference held in Geneva in 1973 has just been published by the ITU. The Acts contains Telegraph and Telephone Regulations which come into force in September 1974, and are published in French, English and Spanish. Each volume costs 17 Swiss Francs from Sales Service, International Telecommunications Union, Place des Nations, CH-1211 Geneva 20, Switzerland.

About People

Howard Steele, ACGI, B.Sc(Eng), FIEE, Director of Engineering of the IBA, was awarded an Honorary Fellowship of the British Kinematograph, Sound and Television Society at the Fellows' Luncheon in May. The award is in recognition of his "unremitting efforts to progress the highest standards of motion picture film technology and usage in colour television broadcasting". Mr Steele played an important part in the selection of the European colour television system and was awarded two Royal Television Society premiums for his contributions.

Senri Miyaoka, manager of television tube development at Sony, received the 1974 Vladimir K. Zworykin Prize Award for his contribution to the development of new concepts in colour television tubes. Mr Miyaoka was responsible for the development of the single-gun, three-beam tube—the Trinitron, released in 1968. An article on this tube by Mr Miyaoka appeared in our December, 1971 issue.