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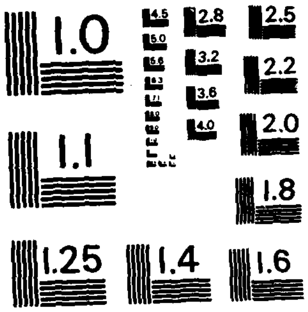

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METEOR SCATTER COMMUNICATION IN AN AIR-GROUND ENVIRONMENT

by

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SUMMARY

Experimental results from forward scattering of high frequency radio signals from meteor trails are described for a ground to ground link. The experimental results are compared with theoretical predictions and close agreement is demonstrated. The design of a very high frequency airborne meteor scatter system is addressed and it is shown to present significant problems, different in nature from those encountered in ground based systems. It is shown that experimental studies of aircraft electromagnetic noise are required before an optimal system can be designed. The reduction in data throughput due to Faraday rotation is also described.

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1 HISTORY

It has been known for many years that electromagnetic waves can be propagated by forward scattering from meteor trails. Early radar observations (Hey and Stuart[1]) in 1947 led to the suggestion in 1954 that they might provide a means of communication (Eshleman and Manning[2]). The first operational meteor scatter system, JANET (Forsyth et al[3]), was implemented in 1957 but was not a complete success. Several relatively successful point-to-point links were, however, implemented between the late 1950s and early 1970s (eg Bartholome and Vogt[4]). In 1960 it was suggested by Hannum et al[5] that the use of meteor trails for air-ground communication should be possible without the need for directional antennas on the aircraft. This view is currently being studied by the Royal Aircraft Establishment (RAE) in the UK and is the subject of the present paper.

2 PHYSICAL CHARACTERISTICS

A small fraction of meteors incident on the atmosphere occur in showers, these being due to groups of particles moving in well defined orbits around the sun. Sporadic meteors are particles which move in random orbits and account for the vast majority of the total incident meteors. The arrival rate is random with a 4:1 variation between the maximum in August and minimum in February. There is a further 4:1 variation between a maximum at around 0600 local time (LT) and a minimum at 1800 LT due to the Earth's rotation. Evaporation begins at a height of about 120 km and most meteors are completely burned out by 80 km. This evaporation process produces ionised trails typically 15-20 km long, with densities of 10^{10} to 10^{18} electrons per metre. Trails with densities in excess of 10^{14}, produced by the larger particles, are termed 'overdense' and can considerably modify the incident wave, owing to interaction between electrons in the trail. Underdense trails, however, provide scattered signals which are remarkably space and time-coherent.

3 A HIGH FREQUENCY GROUND BASED EXPERIMENT

3.1 Description

In order to assess some of the characteristics of meteor scatter propagation, an experimental high frequency (HF) link was set up between Kinloss in Scotland and Farnborough, Hampshire during July 1981 (Richardson[6]). The ground range was 712 km. The Farnborough antenna was a horizontal log periodic with a gain of 12 dBi at the required elevation angle and the Kinloss antenna was a horizontal dipole with a modest gain of 2 dBi to simulate that obtainable on an aircraft. The radiation patterns of both antennas were determined by calibration flights in a helicopter. Transmissions of unmodulated carrier wave were made in both directions at approximately 27 MHz, at eight power levels between 20 W and 820 W, with a minute on - minute off format. Most measurements were conducted in the early morning. The presence of a scattered signal was indicated by an excursion of the receiver automatic gain control (AGC) voltage. By calibrating the AGC response of the receiver, it was possible to obtain a figure for the propagation loss of each trail observed.

3.2 Results

It is interesting to compare the experimental results with theory. Theoretically, the propagation loss due to scattering from an underdense trail is given by the following expression (ie Sugar[7]):

$$\frac{P_R}{P_T} = \frac{1}{32\pi^4}\left(\frac{\mu_0 e^2}{4\pi m}\right)^2 \frac{2\lambda^3}{R_1 R_2(R_1 + R_2)} \frac{G_T G_R q^2 \sin^2\alpha}{1 - \cos^2\beta \sin^2\phi} \exp\left(-\frac{8\pi^2 r_0^2}{\lambda^2 \sec^2\phi}\right) \exp\left(-\frac{32\pi^2 Dt}{\lambda^2 \sec^2\phi}\right) \qquad \text{...... (1)}$$

where P_R = received power (W)
P_T = transmitted power (W)
μ_0 = permeability of free space = $4\pi \times 10^{-7}$ H/m
e = charge on electron = 1.6×10^{-19} C
m = mass of electron = 9.1×10^{-31} kg
λ = wavelength of transmission (m)
R_1 = path length from transmitter to meteor trail (m)
R_2 = path length from meteor trail to receiver (m)
G_T = power gain of transmitting antenna relative to isotropic
G_R = power gain of receiving antenna relative to isotropic
q = line density of electrons in trail (electrons/m)
α = angle between E-vector arriving at trail and the direction from the trail to the receiver (degrees)
β = angle between trail and plane of propagation (degrees)
ϕ = semi-angle of reflection (degrees)
r_0 = initial radius of trail (m)
D = diffusion coefficient (m^2/s)
t = time (s).

We consider a model with a trail of initial radius (Brown and Williams[8]) 1.1 m, line density 10^{13} electrons/m, and $\beta = 90°$, occurring midway between the transmitter and receiver at a height of 100 km and offset 100 km from the centre line. The time, t, taken to cross half of the first Fresnel region is 23.5 μs [6] and the coefficient D is determined empirically (Grossi and Jared[9]) as 13.4 m^2/s. Using these values in equation (1) gives $P_R/P_T = -179.2$ dB. This corresponds well to the most commonly occurring experimental measurement of −178 dB. Immediately a meteor trail is formed, it begins to expand radially by diffusion. The useful lifetime of a trail is of course dependent on range, transmitter power and receiver sensitivity, equation (1). The decay from maximum signal strength is given by the second exponential term in equation (1) such that at time t:

$$\frac{P(t)}{P_{max}} = \exp\left(-\frac{32\pi^2 Dt}{\lambda^2 \sec^2\phi}\right) . \qquad (2)$$

For a fall to half power (-3 dB), equation (2) must equal 0.5, ie

$$t = \frac{0.69\lambda^2 \sec^2\phi}{32\pi^2 D} = 0.14 \text{ s}$$

for the model considered.

The median of observed durations was 0.2 s, which compares quite well with the prediction.

The majority of observations indicate that the arrival times for sporadic meteors are randomly distributed and can, therefore, be described by Poisson statistics. Maslin[10] shows that the probability, p, that the the interval between suitable events is less than T_M seconds is given by:

$$p = 1 - \exp\left[-\frac{HKT_M}{q}\exp\left(-\frac{at}{\tau}\right)\right] \qquad (3)$$

where H = common area of illumination at meteor trail heights, calculated as 8.625×10^9 m^2

K = a proportionality constant, determined experimentally by Hawkins[11] to be 130 m^2/s

a = a variable depending on line density[2], calculated to be 1.03 [6]

τ = time constant of diffusion:

$$\frac{\lambda^2 \sec^2\phi}{16\pi^2 D} = 0.4 \text{ s} . \qquad (4)$$

Rearranging equation (3),

$$T_M = \frac{q}{HK}\exp\left(\frac{at}{\tau}\right)\ln\left(\frac{1}{1-p}\right) . \qquad (5)$$

Taking the median observed duration of 0.2 s and of $p = 0.5$, equation (5) gives a predicted $T_M = 10.3$ s. This is the average waiting time for a whole year, so dividing twice by 2 to account for the daily and annual 4:1 variations, the predicted median waiting time for early morning in July is 2.6 s. The observed median of 2.0 s is, again, consistent with the predicted value.

The experiment has shown that, at least for the conditions investigated, theoretical predictions for propagation loss, link duration and waiting time can be relied upon. The frequency of 27 MHz was used partly on the basis of equipment availability. Further work will concentrate on the very high frequency (VHF) band, where interference from other users, a severe problem during these experiments, will present less of a problem.

4 AIR-GROUND VHF METEOR SCATTER COMMUNICATIONS

4.1 Background

We turn now to the subject of air-ground and ground-air meteor burst communications at VHF. The aircraft, large or small, presents a difficult environment for any radio system and a meteor burst system is no exception to this rule. In particular, the system will be subject to a high aircraft radio noise environment together with low aircraft transmitter powers (<400 W) and aircraft antenna gains (~0 dBi) which are low compared to those available for ground based meteor scatter systems[3,4]. It can be seen that the design of a meteor burst system for airborne use presents a formidable problem.

Most ground based meteor scatter systems utilise frequencies between 40 and 50 MHz[3,4]; this is a compromise primarily dictated by three factors. Firstly, the interfering signals should be kept to a minimum and thus the operating frequency should be above those propagated by normal ionospheric modes. Secondly, the absorption in the D-region should be minimised by using as high a frequency as possible. Thirdly, the throughput should be maximised; under certain assumptions, discussed further in the next section, this occurs when using as low a frequency as possible.

In the remainder of this paper we discuss the relative performance of an air-ground system operating at a conventional frequency of ~40 MHz and a higher frequency of ~70 MHz.

4.2 Information flow rates

The obvious desire to maximise the information flow rate per trail has already been discussed. The average information flow rate per trail, I, is proportional to the bandwidth, B, the duty cycle D_C and some function, $f(S/N)$, of the signal to noise ratio, thus:

$$I = BD_C f\left(\frac{S}{N}\right) . \qquad (6)$$

It can be shown (eg Sites[12]) that

$$D_C = N(q > q_0)\tau = \frac{\lambda^2}{q_0} \qquad (7)$$

where N is the number of trails with q greater than some threshold value q_0. Rewriting P_R in equation (1) as S, the threshold received power, and expressing the background noise power as $B\lambda^n$, when n is real, we have:

$$\frac{S}{N} = \frac{P_T G_T G_R \lambda^{3-n} q_0^2}{B} . \qquad (8)$$

For B and S/N constant it follows from equations (7) and (8) that:

$$I = D_C = (P_T G_T G_R)^{0.5} \lambda^{(7-n)/2} . \qquad (9)$$

For ground to ground links the background noise level is generally assumed to be determined by cosmic noise and as such $n = 2.3$ (Cottony and Johler[13]) and $I \propto \lambda^{2.35}$. On an aircraft, however, the noise level is generally determined by other aircraft installations. Fig 1 shows estimated antenna noise figures for various sources of aircraft noise, together with the cosmic noise figure. Curves C and D are based upon British Standards Institution limits and curves E and F are estimates of worst case aircraft precipitation static noise. On the basis that the latter have been significantly reduced by judicious use of anti-static devices, Maslin[14] proposes curve B as a zeroth order estimate of the aircraft noise figure. This gives $n = 2.7$ and $I \propto \lambda^{2.15}$. As such the ground to aircraft throughput is slightly less dependent on wavelength than is the aircraft to ground link throughput. Until, however, an accurate estimate of the aircraft noise power spectrum has been obtained no firm conclusions can be reached regarding the variation of throughput with wavelength; adherence to curve F, for instance, gives $I \propto \lambda^2$.

Equation (9) has also demonstrated that the throughput is proportional to $(G_T G_R)^{0.5}$. Current estimates place the efficiency of a 70 MHz aircraft slot antenna higher than the corresponding 40 MHz antenna by ~2 dB. Evidently, equation (9) needs to be evaluated as a whole rather than in part. When this is done (for $n = 2.7$) the throughput is ~3 times higher at the lower frequency.

The above analysis takes no account of temperate latitude D-region and auroral D-region absorption which will favour the use of a higher frequency.

4.3 Power link budgets

Having discussed the relative attributes of the two frequencies, operating at a threshold S/N ratio, it is instructive to define this value and conduct power link budgets to ascertain whether it can be met, even at the start of the trail. It is convenient to express the S/N ratio in terms of the ratio E_b/N_0, the energy per bit to noise power spectral density ratio. A threshold value of 13 dB had been adopted for the start of the trail, corresponding to a bit error rate of 1 in 10^4 for frequency shift keying modulation. For illustrative purposes the following analysis considers a fixed length link of 813 km (Farnborough, England to Wick, Scotland). The study of the ground to ground link over this distance provides a good baseline.

This calculation assumes certain model parameters. Firstly, underdense scattering of the wavefield by a line density of 5×10^{13} electrons/m is assumed to take place at an altitude, h, given by Ref 8. The initial radius r_0, is calculated from the same reference and the ambipolar diffusion coefficient, D, is calculated from the equation given by McKinley[15]. Horizontal polarisation is assumed so that $\alpha = 90°$. β, which can vary over the range 0 to 90° is assumed to be 45°, ϕ was calculated using spherical trigonometry. Using these parameters the free space and meteor scatter losses were determined. Included in the link budget is an estimate of the noon temperate latitude D-region absorption, (dB), determined from the equation of Rawer[16] during high magnetic activity over the UK. The 400 W transmitter power corresponds to the maximum aircraft power and feeds a dipole, at optimum height over a perfectly conducting earth, giving

8 dBi gain. The receiving station antenna gain is 18 dBi corresponding to two 4-element stacked YAGIs at optimum height. The receiving station noise figure is cosmic noise limited; the preamplifier noise figure is 1.5 dB at both frequencies. The bit rate is 2400 bits/s.

Table 1 shows that at the start of the trail the losses at 70 MHz are higher than those at 40 MHz but the improved noise performance at 70 MHz together with the reduced D-region absorption offsets this disadvantage. The resulting values of E_b/N_0 are very similar and the threshold value of 13 dB is easily met demonstrating that the construction of a ground to ground link is relatively easy. Table 1 also shows a similar calculation for an aircraft to ground link. The receiving station performance is the same as that described above. Now, however, the aircraft antenna gain is only 2dB at 70 MHz and 0 dB at 40 MHz. Once again we see that the link can be met (but only just) at the start of the trail.

The final step is to investigate the reverse (ground to aircraft) link. In this case the ground transmitter power has been increased to 1 kW; the aircraft antenna gains are again 0 and 2 dBi at 40 and 70 MHz respectively. The aircraft noise performance is based upon Fig 1, curve B which shows a noise factor 30 to 40 dB above an ambient temperature of 290 K at the frequencies of interest. Table 1 shows that the calculation gives a negative E_b/N_0 for this line density and in fact even for $q = 1 \times 10^{14}$ electrons/m, E_b/N_0 is only just positive at 40 MHz.

We conclude that aircraft to ground meteor scatter communication will be possible. In the reverse direction the link requirements will not be met with the estimated aircraft noise performance. The design of an operational system will reflect the accuracy, or otherwise, of these figures.

4.4 Another loss mechanism

A loss mechanism addressed by Cannon[17] is that of Faraday rotation which may result in a minimum coupling condition between the wave and a linearly polarised antenna. At these frequencies the use of a linearly polarised aircraft antenna is almost obligatory. Fig 2 shows the calculated Faraday rotation loss at 40 MHz and 60 MHz for a wave propagating from an aircraft flying a great circle route towards Gibraltar. These calculations were carried out at noon summer solstice and represent great circle propagation with reflection taking place at the path mid-point. The graph shows that significant losses can occur for certain aircraft distances at 40 MHz, but little will be lost at 60 MHz. Luckily, because reflection does not necessarily take place at the centre point of the path but over a large common area meeting certain geometrical constraints[7], system blackout will not occur. It is likely, however, that Faraday rotation losses will cut significant holes, marking regions of progressively reducing attenuation, from this common area. Consequently, a reduced throughput can be expected. It is therefore concluded that the design of an operational meteor scatter system should take into account the problems of Faraday rotation losses and that an air-ground system which operates over variable length links should not utilise frequencies as low as 40 MHz.

5 SUMMARY

The close correspondence between the predicted and experimental results for a ground to ground HF link has provided confidence in the use of the prediction equations in future system design. In addition the design of an airborne meteor scatter system is shown to be more difficult than, and different from, a ground based system.

Table 1

CALCULATION OF E_b/N_0

	Units	Ground to ground		Air to ground		Ground to air	
		40 MHz	70 MHz	40 MHz	70 MHz	40 MHz	70 MHz
Transmitter	dB W	26.02	26.02	26.02	26.02	30.0	30
Feeder losses	dB	-0.5	-0.5	-1.0	-1.0	-0.5	-0.5
Transmit antenna gain	dBi	8.0	8.0	0	2	18	18
EIRP	dB W	33.52	33.52	25.02	27.02	47.5	47.5
Free space and meteor scatter losses	dB	-182.4	-189.9	-182.4	-189.9	-182.4	-189.9
Noon temperate latitude D-region losses	dB	-1.14	-0.39	-1.14	-0.39	-1.14	-0.39
Power at receiver antenna	dB W	-150.0	-156.8	-158.5	-163.3	-136.1	-142.8
G/T	dB/K	-21.8	-15.8	-21.8	-15.8	-64.6	-54.6
C/N_0	dB Hz	56.8	56.0	48.3	49.5	27.9	31.2
(10 log (bit rate))		33.8	33.8	33.8	33.8	33.8	33.8
E/N_0	dB	23.0	22.2	14.5	15.7	-5.9	-2.7
Receive station antenna gain	dBi	18	17	18	18	0	2
Receive station noise figure	dB	15.3	9.7	15.3	9.7	40	32

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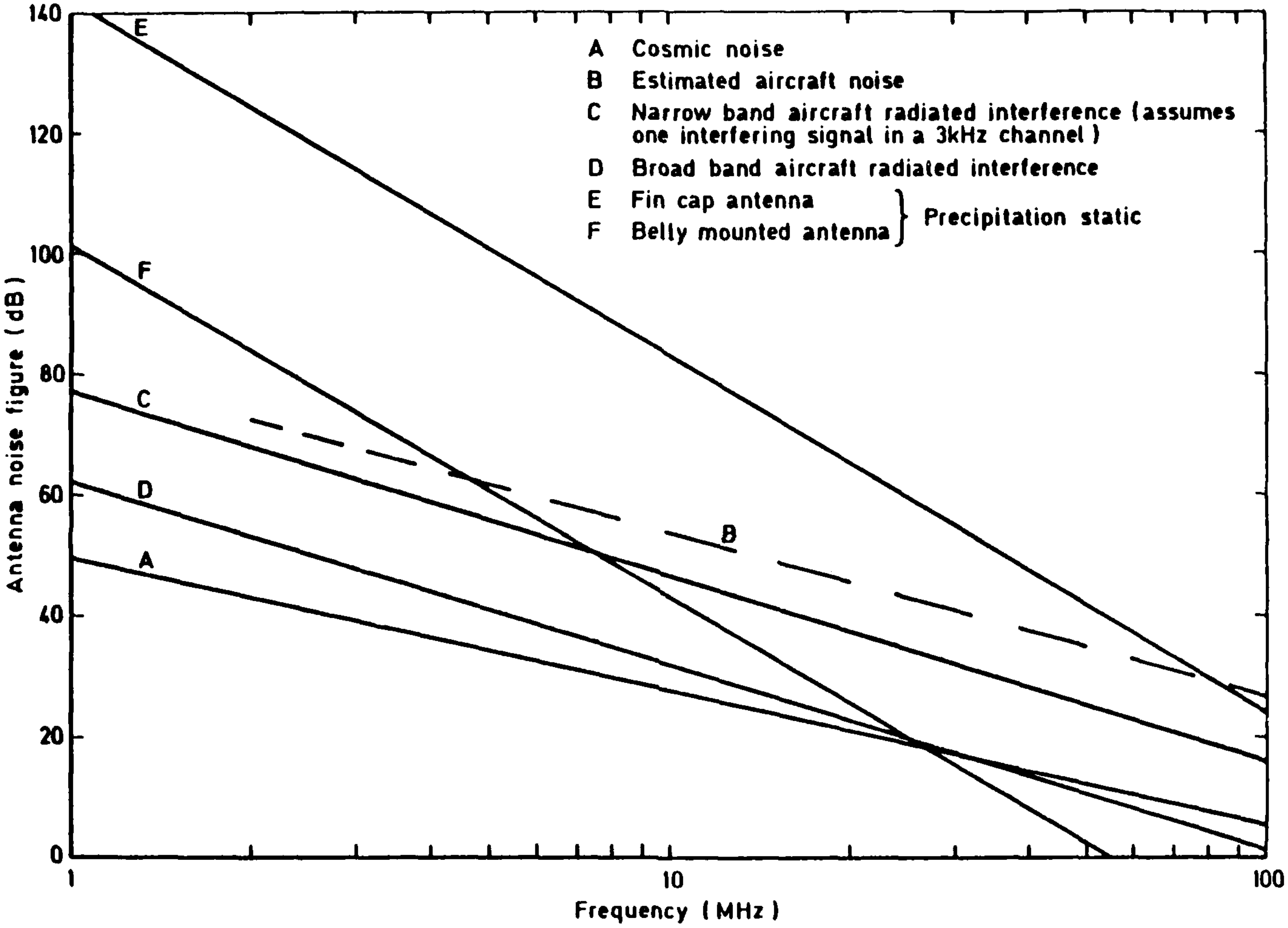

Fig 1 Noise figures for sources of aircraft noise

Fig 2

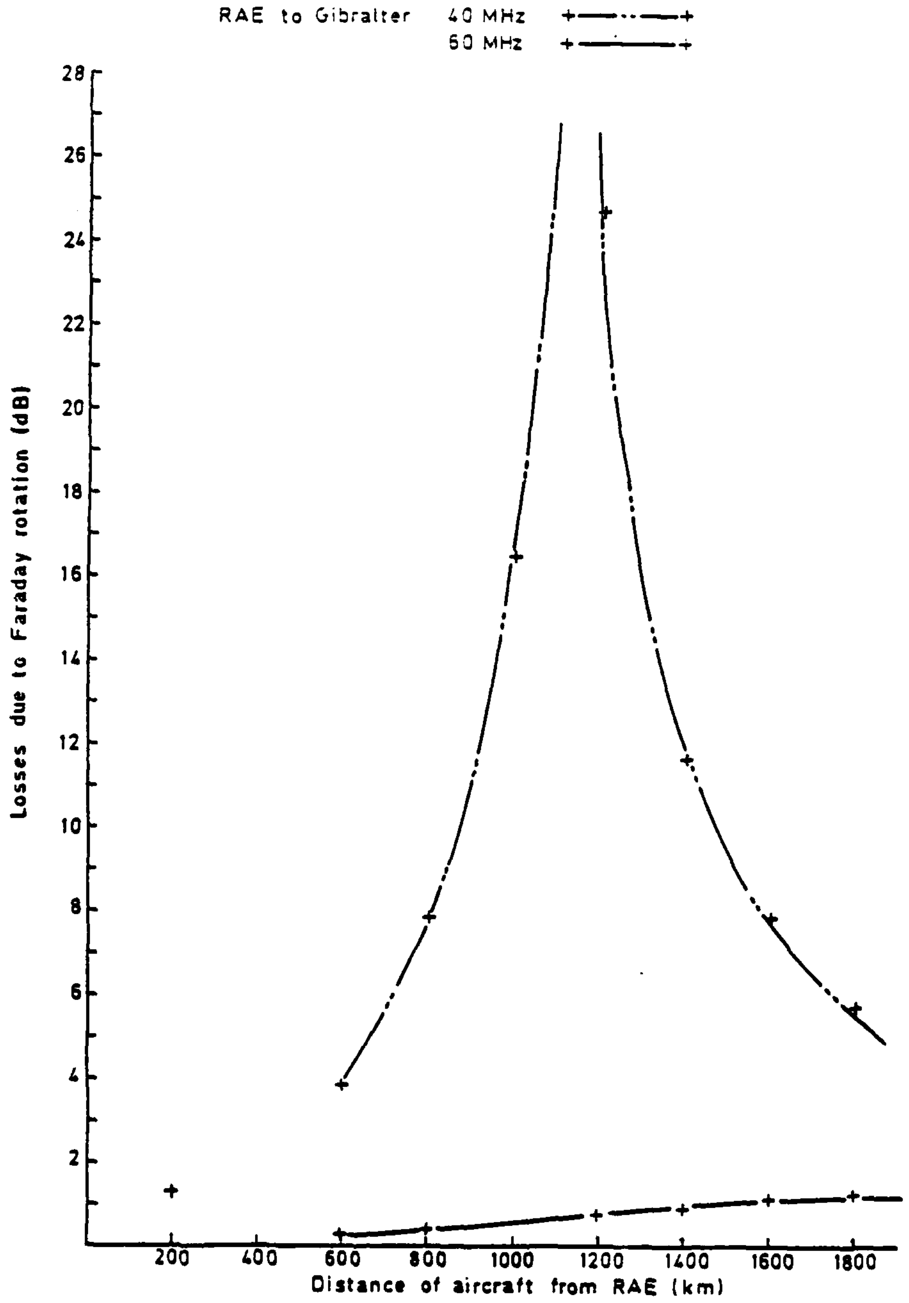

Fig 2 Faraday rotation losses for a linearly polarised receive antenna

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