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A SURFACE-WAVE APPROACH TO HIGH-GAIN ANTENNA DESIGN FOR DATA ACQUISITION BY UHF RADIO TELEMETRY

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A SURFACE-WAVE APPROACH TO HIGH-GAIN ANTENNA DESIGN FOR DATA ACQUISITION BY UHF RADIO TELEMETRY

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Indexing terms: Antennas, Radio telemetry

Synopsis

The phase-velocity characteristics for surface waves on periodic-rod Yagi-Uda structures have been determined at 412 MHz as a function of director length and spacing. Using this approach, a high-gain antenna has been developed for use at data processing centres linked to remote data acquisition points by UHF radio telemetry.

The antenna is characterized by a slow-wave structure having three regions of tapered phase-velocity distribution along its length. The main body phase velocity is selected as a function of antenna length to optimise the gain, and tapered to control sidelobes and bandwidth. A feed taper of lower phase velocity is used to maximise the coupling from the structure to the dipole, and a terminal taper to match the surface wave to free space.

The performance of a folded dipole, a double delta-loop and a full-wave dipole with balun/impedance transformer have been compared as feed elements for the array. Dimensional information is given for a complete 5-wavelength 37-element design having a forward gain of 18 dB relative to an isotropic radiator. The high gain of this antenna allows the use of low powers and simple antennas at the remote transmitters.

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1 Introduction

UHF radio telemetry is appropriate for many situations in which hydrological, hydrodynamic and coastal engineering data are collected at a central location from several dispersed unattended monitoring points. The technique avoids the expense of cabling from the data centre to the individual data acquisition areas, which may be up to 25 km distant and separated by an expanse of sea or inaccessible terrain. The 412 MHz band (λ = 72.8 cm) is allocated for such telemetry, and has the advantage of being relatively interference-free compared with lower frequencies.

Since the data acquisition equipment is generally battery operated, it is desirable that power consumption be minimal to extend the intervals between service visits. Transmitter power outputs used are therefore typically of the order of 1 Watt. Because of the exposed nature of most sites, and of the offshore data collection platforms in particular, small transmitter antennas are desirable as they are less susceptible to damage by tropical storms and large seabirds. As a result of these limitations at the monitoring points, there is a requirement for a high-gain antenna for use at the data collection centre to achieve a received signal-to-noise ratio adequate for an acceptable telemetry data error rate.

2 Required antenna gain

At a range R = 25 km, the free space loss at 412 MHz is

$$20 \log (4\pi R/\lambda) = 113 \text{ dB}$$

It is important to appreciate that, even though the path is line-of-sight, the actual transmission loss is modified substantially from this value by the effects of atmospheric conditions and reflections from the earth's surface.

While the dielectric constant of the atmosphere normally decreases with altitude at a rate of about 7.9×10^{-8} per metre, under conditions of substandard refraction it can increase over a range of height, causing inverse bending of UHF signals away from the earth. Unless the path clearance is large, this phenomenon can transform a geometric line-of-sight path into an obstructed one, resulting in severe fading. To minimise this, it is desirable to allow for first Fresnel zone clearance over an earth of 2/3 true radius, rather than the 4/3 true radius which applies to normal refraction conditions.

Local variations in pressure, humidity and temperature gradient can also result in multipath propagation within the atmosphere. The theoretical maximum bound for the resultant fading is a Rayleigh distribution in which the probability of the field intensity exceeding E is

$$\exp \{ -(E/E_{rms})^2 \}$$

Fades of 10 dB may be expected at 412 MHz for up to 1% of the time during the worst month of a year.

Interference between the direct and ground-reflected waves can considerably alter the resultant field intensity at the receiver antenna, particularly for grazing angles over smooth sea water ($\varepsilon = 80$, $\sigma = 4$ mho/m). The angles of incidence are typically much less than Brewster's angle, so that the reflection coefficients are essentially independent of polarization. Since specular reflection predominates only when the phase deviations are less than about ±90°, most paths over terrain are 'rough' and exhibit reflection coefficients of less than 0.5[(1)].

An elevated receiving antenna site is required to minimise the additional transmission loss due to ground reflection. The antenna mounting position may be adjusted to optimise the signal strength in conditions of local field variation, but for a path over relatively smooth sea water subject to tidal variations in level, severe fading should be anticipated and an additional path loss margin must be allowed for this.

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(1) BULLINGTON, K.: 'Reflection coefficients of irregular terrain', Proc. IRE, 1954, 42, pp. 1258 - 1262

The required antenna gain may be estimated as follows:

Transmitter power output (1W)	+ 30 dBm
Transmitter transmission line loss	- 3 dB
Transmitter antenna gain (rel. isotropic) (3-element)	+ 6 dB
Path loss (25 km free space)	-113 dB
Fading margin (rough terrain)	- 15 dB
Receiver transmission line loss	- 3 dB
Received signal power with an isotropic antenna	- 98 dBm
Receiver noise power in 4 MHz bandwidth with 6 dB noise factor	-102 dBm

Hence received signal-to-noise ratio with isotropic antenna = (-98 + 102)

= + 4 dB

Assuming noncoherent pulse transmission, corresponding data error probability = 0.2

Required antenna gain (rel. isotropic) for 20 dB s.n.r. (data error probability $< 10^{-8}$)

$$G = (20 - 4) = +16 \text{ dB}$$

Corresponding capture area

$$A = G\lambda^2/4\pi = 1.69 \text{ m}^2$$

3 Antenna alternatives

While multi-element curtains of collinear dipoles may be employed to produce the required gain, the phasing-lines of such arrays are somewhat fragile and introduce appreciable loss at 412 MHz, solid-dielectric lines having high attenuation and the typical spacing (3 - 8 cm) of open-wire line being significant relative to the wavelength of 73 cm.

The parabolic reflector type of antenna is also usable at this frequency, but it is less satisfactory at decimetric than at centimetric wavelengths.

For practical sizes the efficiencies obtained are generally less than 50% because the aperture blocking by the relatively large feed is appreciable, and the necessarily primitive nature of the feed results in a reflector illumination which departs significantly from the optimal distribution.

End-fire surface-wave antennas, which can achieve a gain proportional to the length of the slow-wave structure of dielectric positioned in front of the feed, are an attractive alternative, particularly the Yagi-Uda[2,3] type in which the structure is a metal 'artificial dielectric' consisting of a linear near-periodic array of parasitic rod elements. As the structure is entirely conducting, the effects of rain and salt water on its radiation properties are minimal, and since the gain per separate feed is high, several basic antennas may be combined in a plane or volume array to achieve very high gain before phasing and matching problems become severe. The low profile of the Yagi reduces mast-loading due to windage, and the antenna is readily folded for transport and assembled without critical alignment problems. A sturdy construction with good resistance to industrial and marine corrosion is easily produced from aluminium alloy rectangular and round section tubing without special jigs or tools.

The attainable gain (rel. isotropic) being about $G = 10L/\lambda$, a structure of length $L = 4\lambda$ is indicated for the desired figure of 16 dB. A 5-wavelength antenna has been designed to ensure that the target performance is exceeded.

4 Design approach

While Yagi-Uda antennas of 2 or 3 elements admit to fairly detailed analysis[4,5], the design of large arrays of 30 or more elements has generally been rather empirical. The problem is that several principal interdependent

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(2) YAGI, H.: 'Beam transmission of ultra-short waves', Proc. IRE, 1928, 16, pp. 715 - 741

(3) UDA, S. and MUSHIAKE, Y.: 'Yagi-Uda Antenna', (Sasaki, Sendai, Japan, 1954)

(4) WALKINSHAW, W.: 'Theoretical treatment of short Yagi aerials', Jour. IEE, 1946, Part IIIA, 93, pp. 598 - 614

(5) Reference (3), Chapter 9

performance parameters:

Forward gain

Front/back ratio

Radiation pattern (beamwidth and sidelobe structure in at least the two principal planes)

Cross-polarization level

Feed impedance (VSWR)

Frequency response of gain, radiation pattern and VSWR

Windage, mechanical rigidity and efficiency of use of material

require to be optimised by the control of a plethora of antenna design variables, such as:

Total antenna boom length

Reflector configuration and dimensions

Feed type and dimensions

Reflector/feed spacing

Director diameter (usually constant for one antenna)

Director lengths (usually varied)

Director spacings (usually non-uniform along the boom)

Since each of the performance parameters is a complicated function of all of the design variables, the designer of such antennas is evidently faced with a rather formidable optimisation task. The approach we have followed is to allow the following simplifying initial assumptions:

1) The feed and reflector may be considered as a unit which can be optimised before the attachment of the slow-wave structure.

2) The contribution of the slow-wave structure to the antenna characteristics is determined only by the phase velocity distribution of the surface wave which propagates along it, and not by the particular combination of structure dimensions which results in that distribution.

While (2) is hardly accurate when considering antenna bandwidth (the director dispersion characteristic being dependent on the structure configuration), the bandwidth of 1 - 2% required for telemetry at Megabaud rates is easily attained.

These assumptions allow a methodical approach to an initial design to be implemented, and they can be discarded in the final phase of detailed tuning of the complete antenna.

5 Reflector

While an ideal reflector would require an unbounded perfectly conducting plane, a minimum reflector can be made with a single rod element of length exceeding $\lambda/2$. As a compromise solution, we have employed a reflector of area λ^2 consisting of a square grid of 9 rods of 0.953 cm (0.013 λ) diameter at a spacing of 8 cm (0.11 λ). The power leakage through such a grid(6) is calculated to be less than -13 dB, so that the reduced windage compared with a solid sheet or mesh is obtained with negligible loss in reflection efficiency.

The angle between each half-plane of the reflector and the boom can be adjusted, as also the distance of the reflector from the feed. For a reflector/feed spacing of about $\lambda/4$ (18 cm), the effect of these adjustments on the antenna gain is not critical so that they may be altered to optimise the impedance matching.

6 Slow-wave structure

The slow-wave structure may be divided into three distinct regions, characterized by different phase velocities distributions (see Fig. 1). In the main body region extending over about 75% of the length of the structure, the mean phase velocity has a value selected as a function of the total antenna length to optimise the gain(7). For a 5λ (3.64 m) antenna, a value of $\lambda_c/\lambda_z = 1.06$ is appropriate, where λ_z is the wavelength of the surface wave supported by the structure.

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(6) MUMFORD, W.W.: 'Some technical aspects of microwave radiation hazards', Proc. IRE, 1961, 49, pp. 427 - 447

(7) EHRENSPECK, H.W. and POEHLER, H.: 'A new method for obtaining maximum gain from Yagi antennas', IRE Trans., 1959, AP-7, pp. 379 - 386

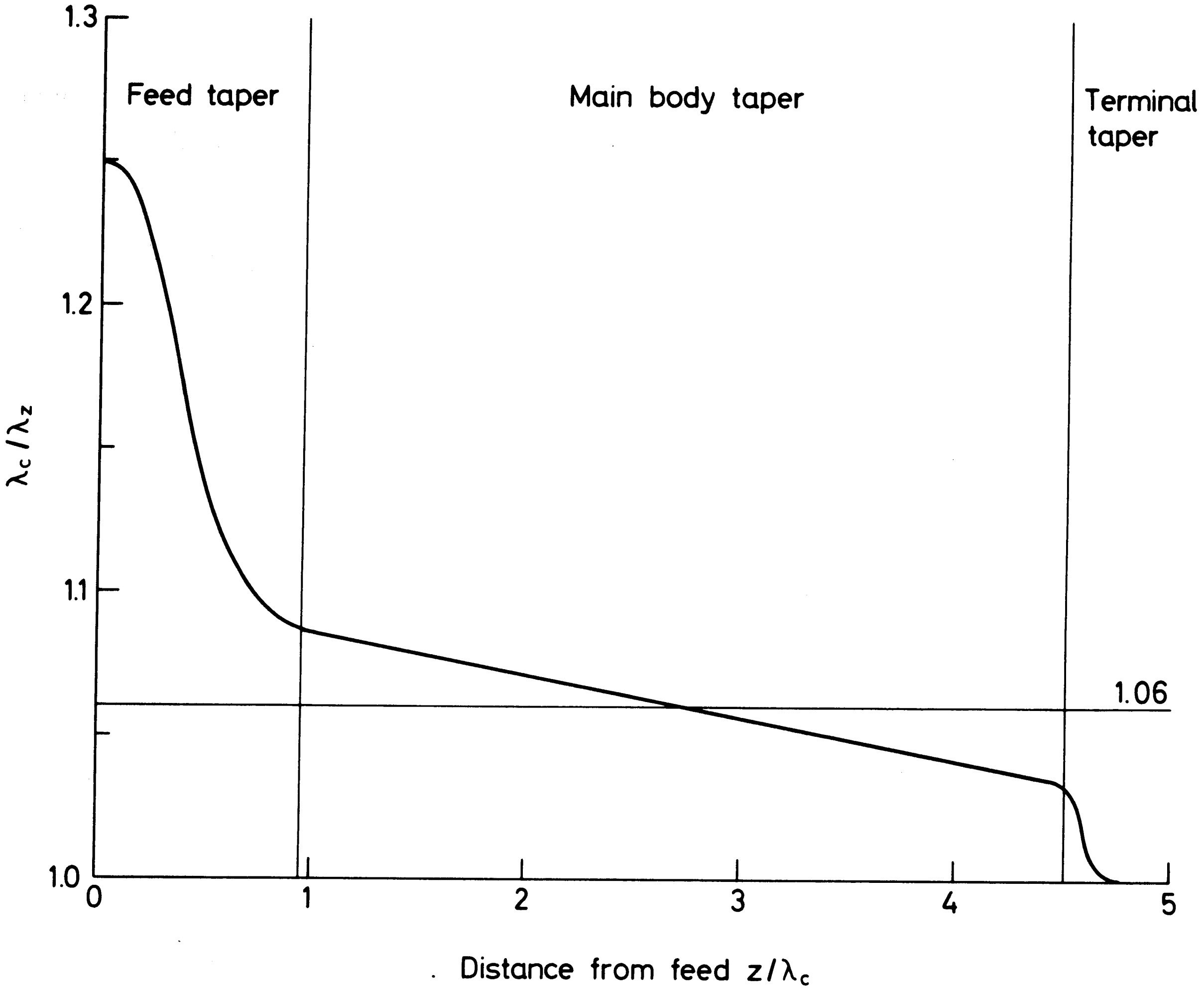

Fig. 1

Target phase velocity ratio distribution along slow-wave structure

λ_c = free space wavelength λ_z = surface wavelength

A total phase velocity taper[8] of 5% is then applied to this region to reduce the amplitude of the first sidelobes and broaden the bandwidth at the cost of a negligible reduction in gain. The phase velocity tapering is achieved by progressively altering the spacing of the directors, rather than their length, as it proves more economical in manufacturing to drill the boom with non-uniform spacing than to cut and stock a large variety of director lengths.

For maximum coupling between the surface wave on the structure and the feed, a lower phase velocity is desirable, corresponding to $\lambda_c/\lambda_z > 1.2$. The transition is effected by progressively diminishing the phase velocity in a feed taper region extending over 20% of the length of the antenna forward of the feed. In this case progressively increasing director lengths are used as well as diminishing director spacings, for control by director spacing alone would require an excessively large number of directors close to the feed to achieve the required reduction in phase velocity.

Finally, over the 5% of antenna length remote from the feed, a terminal taper is created by increased director spacing to match the free space wave to the surface wave with minimum reflection. At the junctions between the terminal taper, the main body, and the feed taper regions of the complete slow-wave structure, the phase velocity transitions are tapered to minimise discontinuities.

7 Phase velocity characteristics

To determine the element geometry required for the desired phase velocity distribution, measurements of phase velocity ratio have been made for surface waves on slow-wave structures at 412 MHz.

The measurement rig consists of a 5λ boom carrying a reflector at one end and a feed dipole at the other. Between the dipole and reflector

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(8) SENGUPTA, D.L.: 'On uniform and linearly tapered long Yagi antennas', IRE Trans., 1960, AP-11, pp. 11 - 17

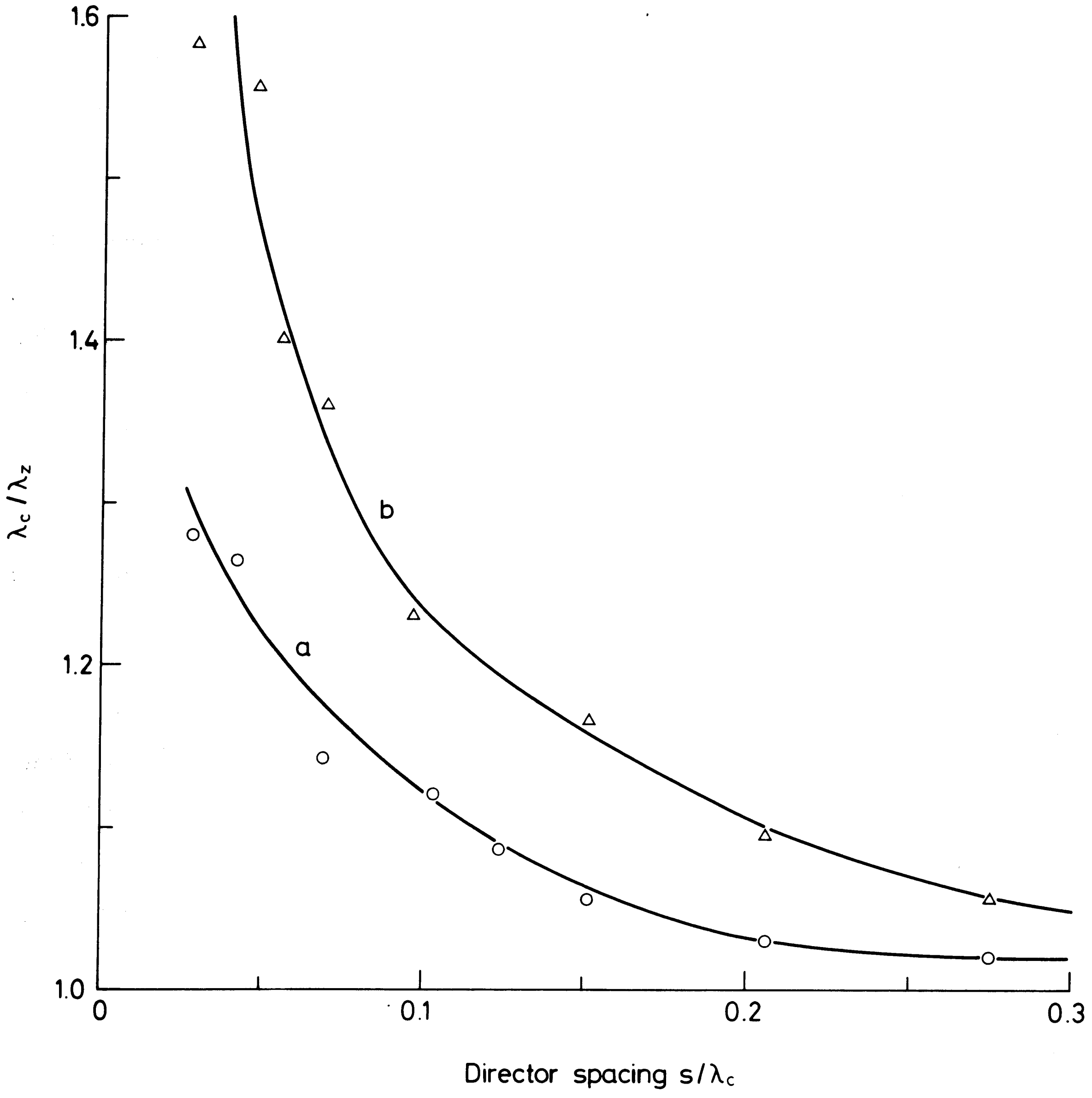

Fig. 2

<u>Phase velocity ratio characteristics for slow-wave structures at 412 MHz</u>

λ_c = free space wavelength λ_z = surface wavelength

Director diameter 6.35 mm (0.0087λ)

Director length a) 27 cm (0.371λ) b) 30 cm (0.412λ)

were configured a series of uniform periodic rod structures of different lengths and spacings. The surface wave launched on the structure by the dipole propagates to the opposite end where it is reflected back along the same structure, setting up a standing-wave pattern.

Using a 1 kHz modulated 412 MHz source of power +10 dBm, the nodes of the standing-wave at half-wavelength intervals are readily detected by a VSWR amplifier using a crystal detector coupled to a short (2 cm) probe. The fields of the higher spatial harmonics of the surface wave attenuate rapidly in the direction transverse to the boom, so that when the probe is moved at a distance from the tips of the elements it detects primarily the field of the fundamental Hartree component. The wavelength measurement is made over several nodes towards the reflector end of the structure, where the surface wave is well established. An open test site was used to minimise errors due to standing-waves set up by reflections of the radiation field.

Fig. 2 shows the resulting phase velocity ratio characteristics for 6.35 mm (0.0087 λ) diameter directors of length 27 cm (0.371 λ) and 30 cm (0.412 λ), for a range of spacings sufficient to meet the requirements of the target distribution of Fig. 1.

8 Feed

It has been reported[9] that a 1 or 2 dB increase in gain is attainable with a complete Yagi-Uda array when the directivity of the feed itself exceeds that of a dipole by a like amount. Three types of feed were therefore evaluated for the antenna - a folded half-wave dipole, a double delta-loop, and a full-wave dipole with balun/impedance transformer.

Folding of the dipole increases the impedance by a factor of 4 to about 300 Ω for the feed alone, which allows tight coupling to the

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(9) SIMON, J.C. and WEILL, G.: 'Un nouveau type d'aérien à rayonnement longitudinal', Ann. Radioélectricité, 1953, 8, pp. 183 - 193

director structure to be made before the impedance falls to 50 Ω. The double delta-loop and the full-wave dipole, used alone, exhibit a small gain relative to the half-wave dipole and also have broader bandwidth. The double delta-loop was connected directly to 50 Ω coaxial at its centre points so that the upper and lower loops are effectively in parallel and each fed at an apex, resulting in horizontal polarization. The full-wave dipole was connected via a half-wave coaxial-line balun. The velocity factor of the solid-dielectric coaxial used was measured as 0.67, resulting in a balun loop length of 24.4 cm. The balun causes the potentials at the inner ends of each half-wave fan section of the dipole to be equal and opposite and balanced to ground, while the impedance presented to the unbalanced feeder is reduced by a factor of 4.

Each of the feed configurations was brought to resonance at 412 MHz by tuning the dimensions while observing the ratio of reflected to incident power by detectors connected to the ports of a coaxial dual directional coupler. A sweep oscillator capable of covering the range 10 - 1300 MHz was used as RF source in conjunction with a swept amplitude analyzer/oscilloscope and external 27.8 kHz PIN-diode absorptive modulator. Final adjustments were made with the different feeds coupled to the slow-wave structure, when the feed taper and reflector geometry were optimised for each for maximum gain and acceptable impedance matching.

9 Performance measurement

For the measurement of gain and radiation pattern, the antennas were evaluated on a test range of length exceeding 50 wavelengths. At this distance, the phase difference between the signal from the test source received at the centre of the antenna and at the periphery of its capture area is $360(A/8\lambda R)^{\circ} = 3.1^{\circ}$ $(0.09\ \lambda)$. This phase difference is small enough for the wavefront illuminating the antenna to be considered planar, so that accurate Fraunhofer patterns are obtained. To minimise field non-uniformities due to ground reflections, the transmitting and receiving antennas were mounted on two roof areas separated by an intervening space of low ground. An underslung support boom was used to avoid aperture blocking by the mast.

For frequency response measurements, it is desirable to use a transmitting antenna of very broad bandwidth so that the effect of adjustments to the receiving antenna can be observed directly. A biconical dipole[10] was designed for this purpose, each cone being formed from a skeleton cage of copper wire covered with fine brass mesh. The characteristic impedance of such a dipole[11] being 120 $\log_e \cot(\theta/4)$, a very large flare angle $\theta = 90^\circ$ was used to keep the impedance low (106 Ω) while retaining the broadband properties. The overall length of the dipole was $\lambda/2$ at 412 MHz, which gave a ± 1 dB bandwidth from 300 to 550 MHz. When frequency response was not being studied, a more directive transmitting antenna than the biconical dipole was used to minimise site reflections.

While reflectometer methods were used for impedance matching, radiation measurements were made by feeding the source antenna from the sweep oscillator and observing the signal received by the test antenna with the analyzer. The drive from the analyzer to the modulator and the sweep, blanking and frequency-marker signals from the oscillator to the analyzer were sent by coaxial cables laid between the transmitter and receiver sites.

On the test range it was found that the three antennas had their maximum gain at the design frequency of 412 MHz. After individual optimisation of the feed tapers and reflector, the gains of all three were equal within ± 0.5 dB, and exceeded 16.5 dB relative to a $\lambda/2$ dipole (i.e. $G > 18$ dB). Fig. 3 shows that the frequency responses differed substantially, however, the full-wave dipole having the broadest bandwidth and the antenna with the $\lambda/2$ folded dipole being the most sharply tuned.

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(10) SILVER, S.: 'Microwave antenna theory and design', (McGraw-Hill, New York, 1949)

(11) PAPAS, C.H. and KING, R.: 'Input impedance of wide-angle conical antennas fed by a coaxial line', Proc. IRE, 1949, 37, pp. 1269 - 1271

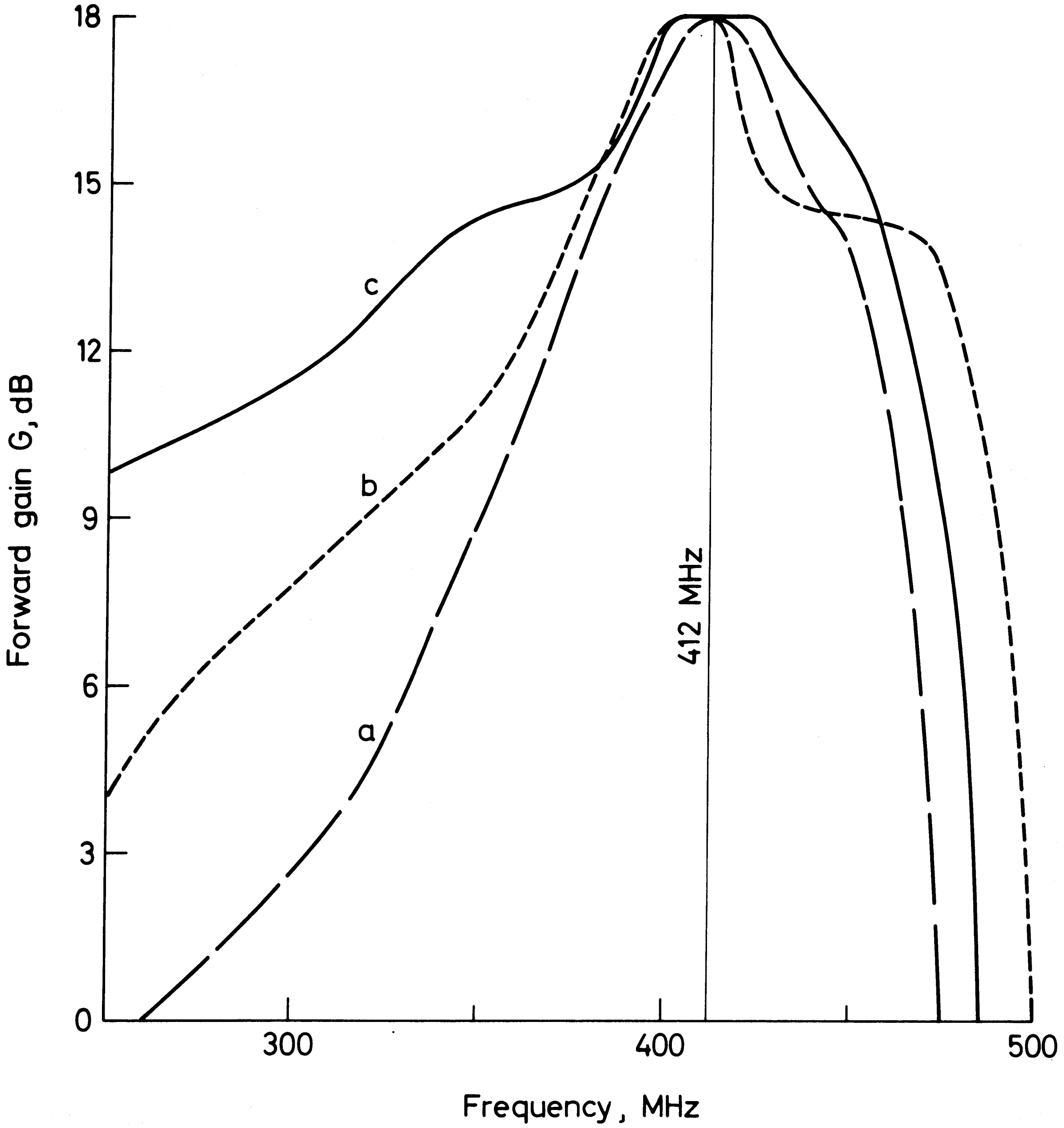

Fig. 3

Frequency response characteristics

5λ antenna with feed type a) folded λ/2 dipole
b) double delta-loop
c) full-wave dipole with balun/impedance transformer

All the antennas exhibit the relatively sharp cut-off above the design frequency, and more gradual fall in gain at low frequencies, which is characteristic of Yagi-Uda structures.

Our results therefore suggest that when the slow-wave structure of a Yagi-Uda antenna is several wavelengths long, so that the capture area is large relative to that of the feed alone; and when there is a feed taper configured for strong coupling to the surface wave, then the total antenna gain is almost independent of limited variations in the feed directivity. The folded dipole required a pronounced feed taper for optimum coupling, and gave maximum gain with the reflector angled in the form of a 90° corner. Both the double delta-loop and the full-wave dipole were optimised with moderate feed tapers and there was no increase in gain on reducing the reflector angle from 180°.

Of the different configurations studied, the antenna with full-wave dipole feed proves the most attractive, and full dimensions for this design are given in Table 1. The completed antenna is shown in Fig. 4. Even when the broader bandwidth of this antenna is not essential to the application, it has the desirable property of minimising the effects of detuning caused by physical damage or manufacturing tolerances. Production of the plane reflector is more economical than that of the angled type required by the folded dipole, while the feed itself is more easily fabricated than the double delta-loop.

The balun, which is incorporated incidentally in this design because of the requirement for a feed impedance transformation, eliminates signal currents on the outside of the coaxial shield. This minimises beam squint due to interaction with the radiation field and is particularly desirable where matching and phasing lines are to be used in the construction of a large array of the basic antennas.

The complete E-plane radiation pattern for this antenna is shown in Fig. 5. The first-order sidelobes at ±35° are 18 dB down from the main beam.

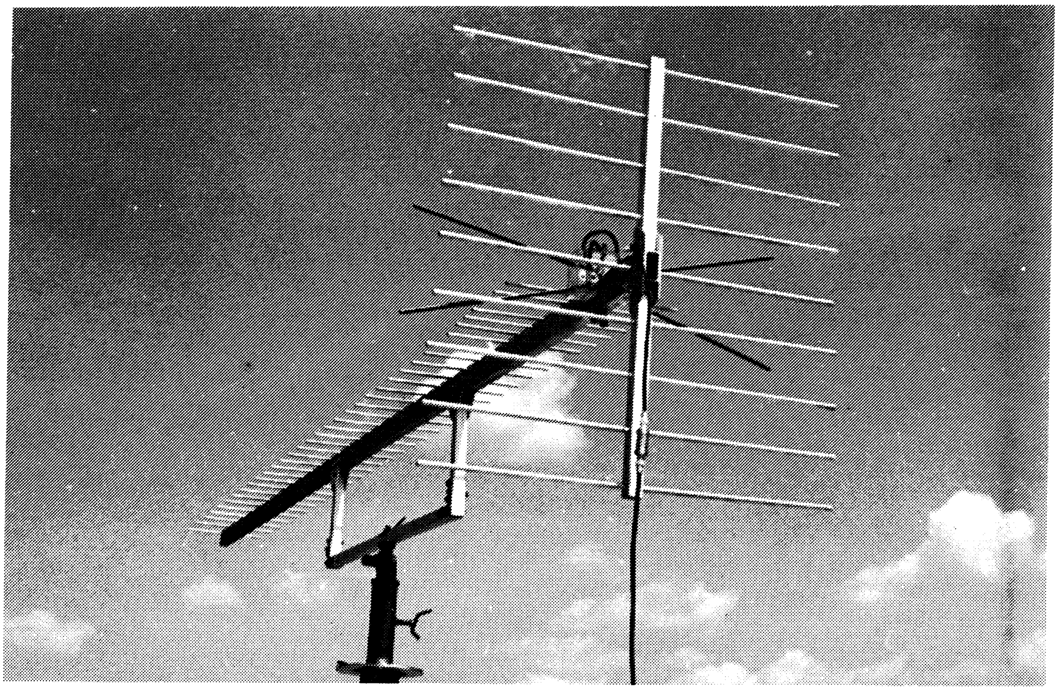

Fig. 4

5λ 37-element antenna with full-wave dipole feed

Table 1 412 MHz 37-ELEMENT ANTENNA

Dimensions in cm

Reflector

Planar grid type on 2.54 × 2.54 × 75 central support

No. of elements 9

Element diameter 0.953 length 73 spacing 8.0

Reflector/feed spacing 18.2

Feed

Full-wave planar 2-element fan-type dipole centre-fed by 4 : 1 impedance transformer/balun

Element diameter 0.635 length (overall) 69.5

Fan separation angle 30°

Balun length (0.67 velocity factor coaxial) 24.4

Slow-wave structure

Boom 2.54 × 5.08 × 366 (2.54 dimension in director plane)

No. of directors 35 diameter 0.635

Director lengths (numbered consecutively from the feed)

Director 1:	33	Director 2:	32.5	Director 3:	32
Director 4:	31	Director 5:	30	Director 6:	29
Director 7:	28	Directors 8-35:	27		

Element spacings (Feed - Director 1 - Director 2 - ... - Director 35)

6.2	6.2	6.2	6.3	6.3	6.4	7.0
8.0	8.6	8.8	9.0	9.1	9.2	9.4
9.5	9.6	9.7	9.9	10.0	10.1	10.2
10.4	10.6	10.8	11.0	11.1	11.4	11.7
12.1	12.2	12.6	12.8	13.0	13.5	17.5

Characteristics

Forward gain 18 dB Front/back ratio 30 dB Feed impedance 50 Ω

Beamwidth 27° First-order sidelobes 18 dB down at ±35°

Bandwidth (3 dB) 374 - 454 MHz Flat (0.1 dB) 402 - 424 MHz

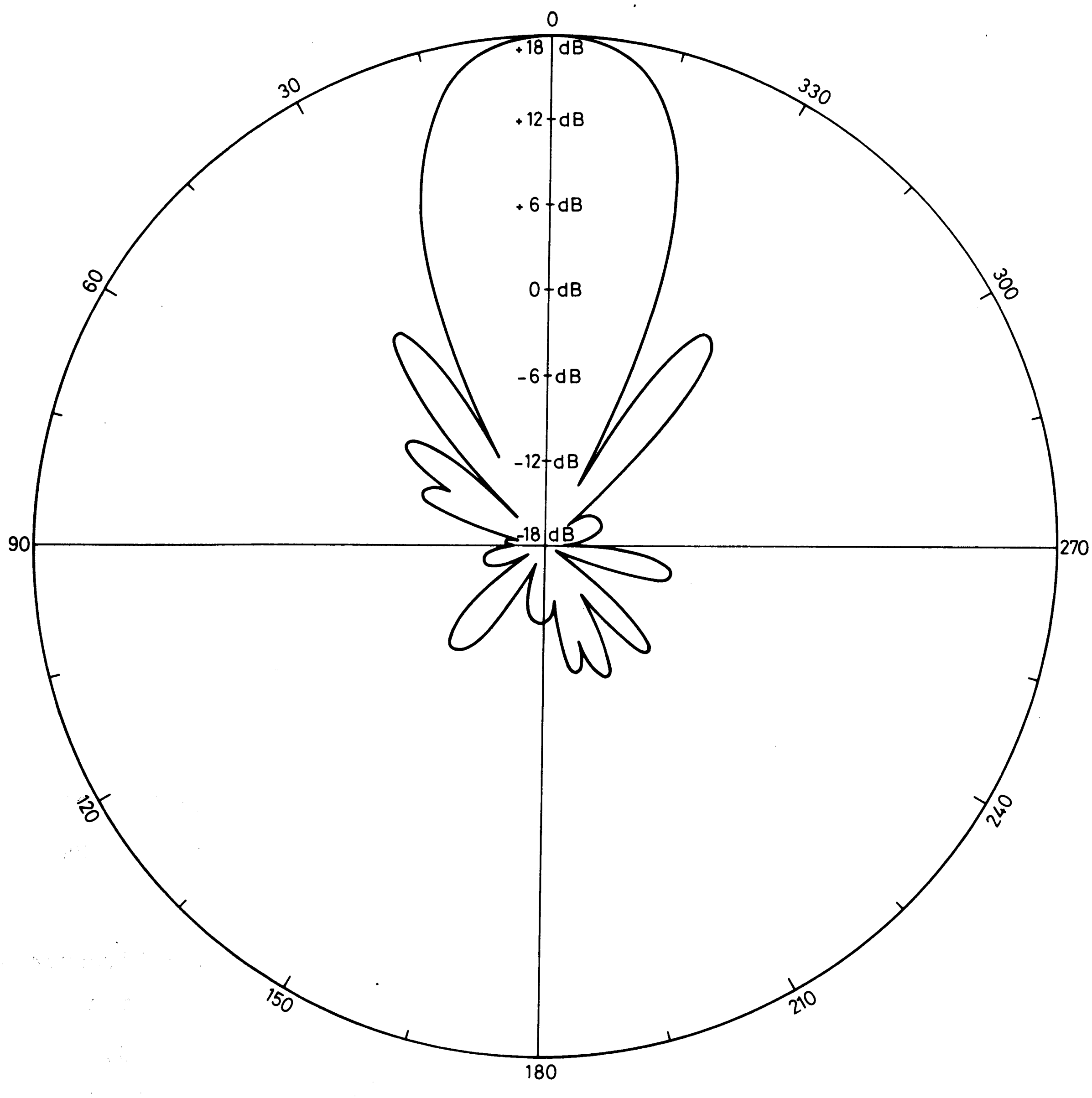

Fig. 5

E-plane radiation pattern

5λ antenna with full-wave dipole feed

10 Conclusion

The surface wave approach described leads to a methodical procedure for the design of high-gain UHF antennas with a minimum of empirical work. A prototype 5-wavelength 37-element design for the 412 MHz radio telemetry band has been developed by the application of the procedure, and a forward gain of 18 dB attained. The antenna also has a high front/back ratio (30 dB), a broad bandwidth (80 MHz) and a clean radiation pattern with a beamwidth of 27°. Employed at a hydrological or coastal engineering data centre, it allows the collection of data at extended range from remote monitoring points using simple antennas and low power transmitters.

11 Acknowledgments

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