Table 3
Dimensions of a 27-Element 432-MHz Yagi

Element	*Length (mm)*	*Spacing (mm)*
REF1-4	345	130
DE	328	—
D1	309	55
D2	305	125
D3	300	150
D4	296	175
D5	294	195
D6	292	210
D7	290	220
D8	290	230
D9	285	240
D10	285	250
D11	285	260
D12	280	265
D13	280	270
D14	280	275
D15-17	280	280
D18-23	275	280
D24,25	270	280

Note: Boom is 20 mm square. Elements are 4 mm diameter and mounted through the boom but insulated by shoulder washers. Feed system is a folded dipole. There are four reflectors.

Table 4
Dimensions of a 26-Element 1296-MHz Yagi

Element	*Length (mm)*	*Spacing (mm)*
REF	118.0	50
DE	110.0	—
D1	104.0	18
D2	102.5	42
D3	101.0	50
D4	99.5	58
D5	98.0	65
D6	97.0	70
D7	96.0	73
D8	95.0	76
D9	94.0	80
D10	94.0	83
D11	93.0	86
D12	93.0	90
D13	92.0	92
D14	92.0	92
D15	92.0	92
D16-18	91.0	92
D19-21	90.0	92
D22-24	89.0	92

Note: Boom is 0.5 inch (12.7 mm) square. Elements are 4 mm diameter and mounted through the boom with full electrical contact (not insulated). Feed system is a folded dipole.

Table 5
Dimensions of a 48-Element 1296-MHz Yagi

Element	*Length (mm)*	*Spacing (mm)*
REF	124	50
DE	110	—
D1	110	18
D2	109	42
D3	108	50
D4	107	58
D5	106	65
D6	105	70
D7	104	73
D8	103	76
D9	102	80
D10	102	83
D11	101	86
D12	101	90
D13	101	92
D14-16	100	92
D17-20	99	92
D21-25	98	92
D26-31	97	92
D32-39	96	92
D40-46	95	92

Note: Boom is 15 mm. Elements are 2 mm diameter and mou through the boom with full electrical contact (not insulated). Feed system is a folded dipole.

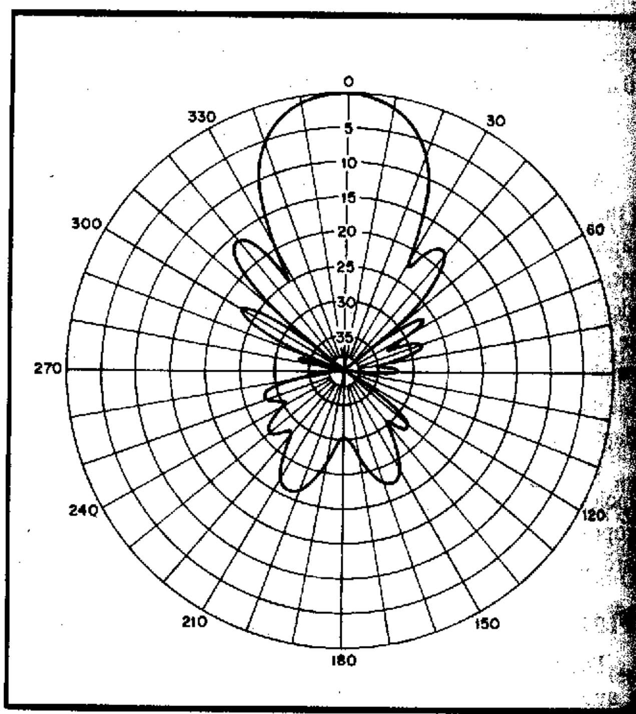
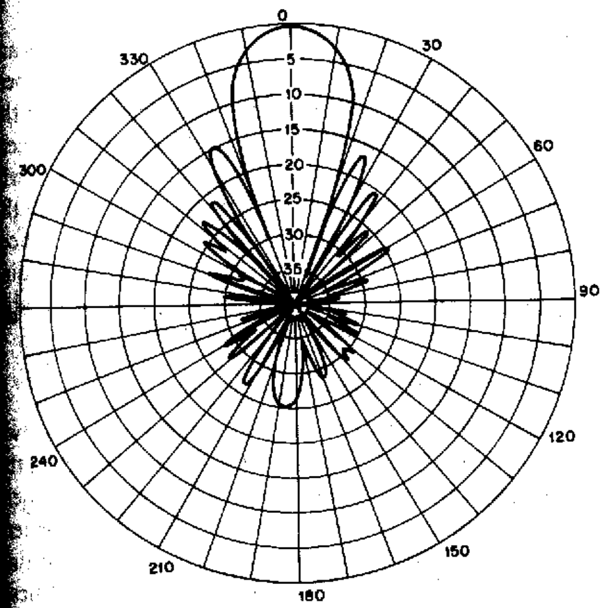
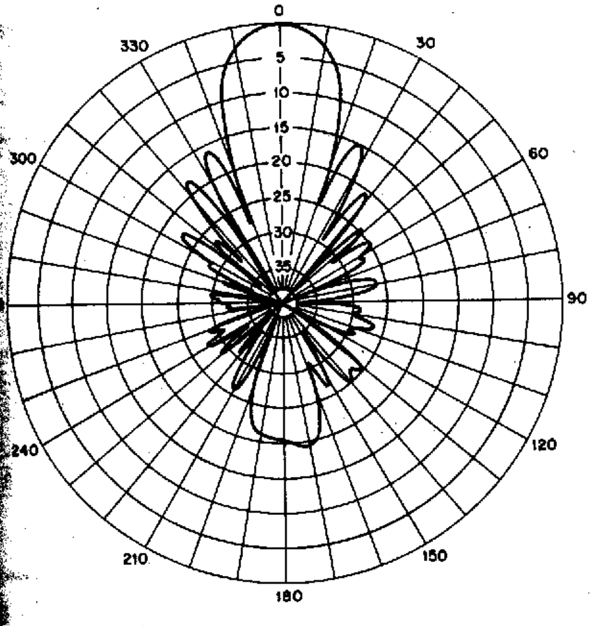


Fig 10—Measured E-plane pattern of the 14-elemen 70-cm Yagi in Table 2.



11—Measured E-plane pattern of the 27-element, cm Yagi in Table 3.



12—Measured E-plane pattern of the 26-element, 23 cm Yagi in Table 4.

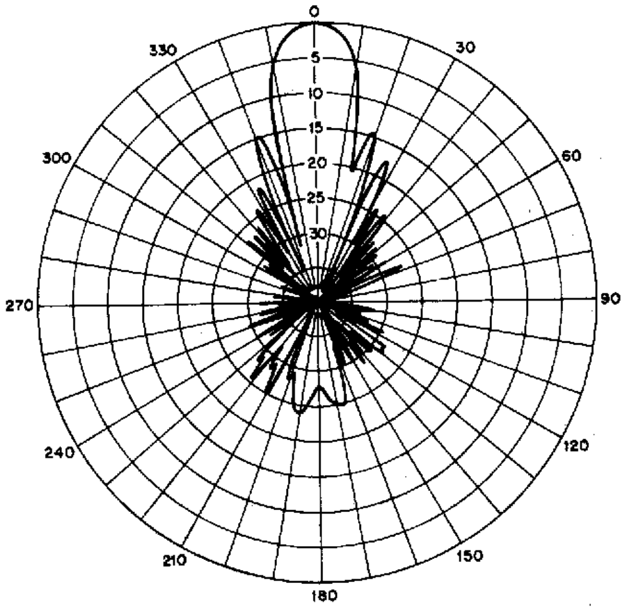


Fig 13—Measured E-plane pattern of the 48-element, 23-cm Yagi in Table 5.

1296 MHz. If minor differences appear between calculated and stated dimensions, they are of no consequence to performance.

STACKING AND POWER DIVISION

Stacking Gain

Perhaps the easiest way of explaining stacking gain is through the concept of effective areas. If two antennas are separated far enough in a field (so the effective areas do not overlap), they will capture twice the power of one. Since antennas function the same way on reception and transmission, the power is doubled (+3 dB) in both cases. The necessary stacking distance is determined by the size and shape of the effective areas (treated later in the *Optimum Spacing* section).

Stacking Pattern Formation

In contrast to gain, radiation pattern formation is more easily understood in the transmitting mode. If power from one source is coherently radiated by two antennas, there will be regions of power addition and cancellation, depending on phase relationship. The power emanating from point sources P_1 and P_2 in Fig 14 (equal power, equal phase) will add up at all points that are equidistant from both sources; these points all lie on the horizontal

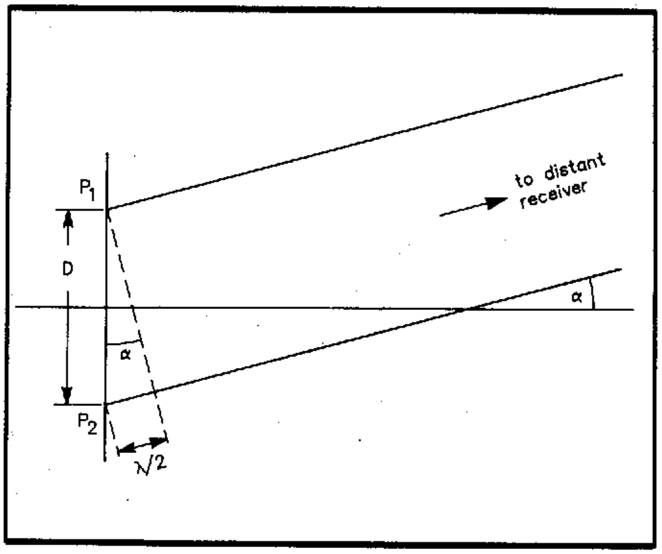


Fig 14—Condition for phase cancellation of radiation from two point sources, P_1 and P_2, separated by distance, D.

axis. Power will also add in all points where the difference in distance to both sources is a multiple of 1 λ (phase difference = 360°, 720°, and so on).

Cancellation will occur where the path difference is λ/2 or odd multiples thereof (phase difference = 180°, 540°, and so on). The associated directions indicated by the angle α can be calculated from Fig 14 with simple geometry. For the mth lobe (field maximum):

$$\alpha_m = \frac{m\,\lambda}{D} \qquad \text{(Eq 6)}$$

For the nth null (field cancellation):

$$\alpha_n = \frac{(n - 0.5)\,\lambda}{D} \qquad \text{(Eq 7)}$$

where D is the distance between the two point sources. Depending on the ratio of D to λ, there will be a sequence of nulls and lobes when α is altered, forming a radiation pattern. If there are more than two sources field relationships become more complicated. Numerous minor lobes are formed by partial phase addition and cancellation.

The Superimposition Principle

Thus far only point sources (isotropic radiators) have been considered. The previously described procedure can also be used to calculate the H-plane patterns of dipoles stacked in a row, since they look like point sources when viewed from the end. For the corresponding E-plane pattern we must consider the patterns of each individual dipole. There is no radiation off the ends of a dipole; even if a like arrangement of point sources produced a lobe in this direction, it would be suppressed. Therefore, the E-plane pattern of a row of dipoles looks like that of a row of point sources superimposed on the pattern of a dipole. This principle holds true for groups of any of antenna, even for groups of groups.

If, for example, two Yagis are stacked and we to know the pattern in the stacking plane, we must impose the pattern of two imaginary point sources same spacing with a Yagi pattern in the same plane. radiation from the point sources would cancel, the be no radiation from the Yagi array. Obviously, individual Yagi patterns have strong minor lobes, are they will coincide with lobes from the imaginary sources and produce "grating lobes" of consid strength, far off the desired beam heading.

Optimum Spacing

The simplest case of stacking involves just antennas. Theoretically, the best spacing occurs whe effective apertures just meet. At smaller spacings would be a loss of capture area; at larger spacings would be no sacrifice in gain, but an unnecessary spli up of the pattern (and additional loss in the phasing li The optimum distance (D_{opt}), based on the assumpti a circular capture area determined from real gain, out to be

$$D_{opt} = \frac{\lambda}{2 \sin\left(\frac{\phi}{2}\right)}$$

where ϕ = the half power beamwidth. For long Ya $< 30°$), D_{opt} is equal to 57 λ/ϕ. Computer simulatio practical measurements have confirmed this to be distance beyond which there is no noticeable gain incr

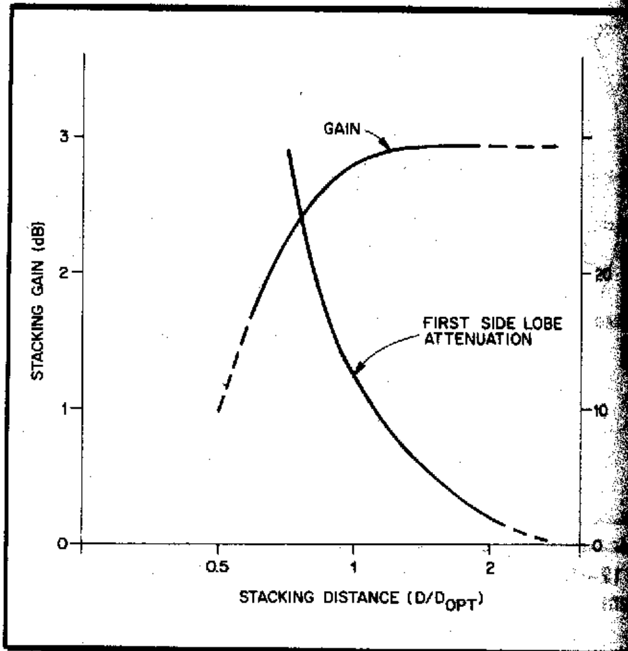
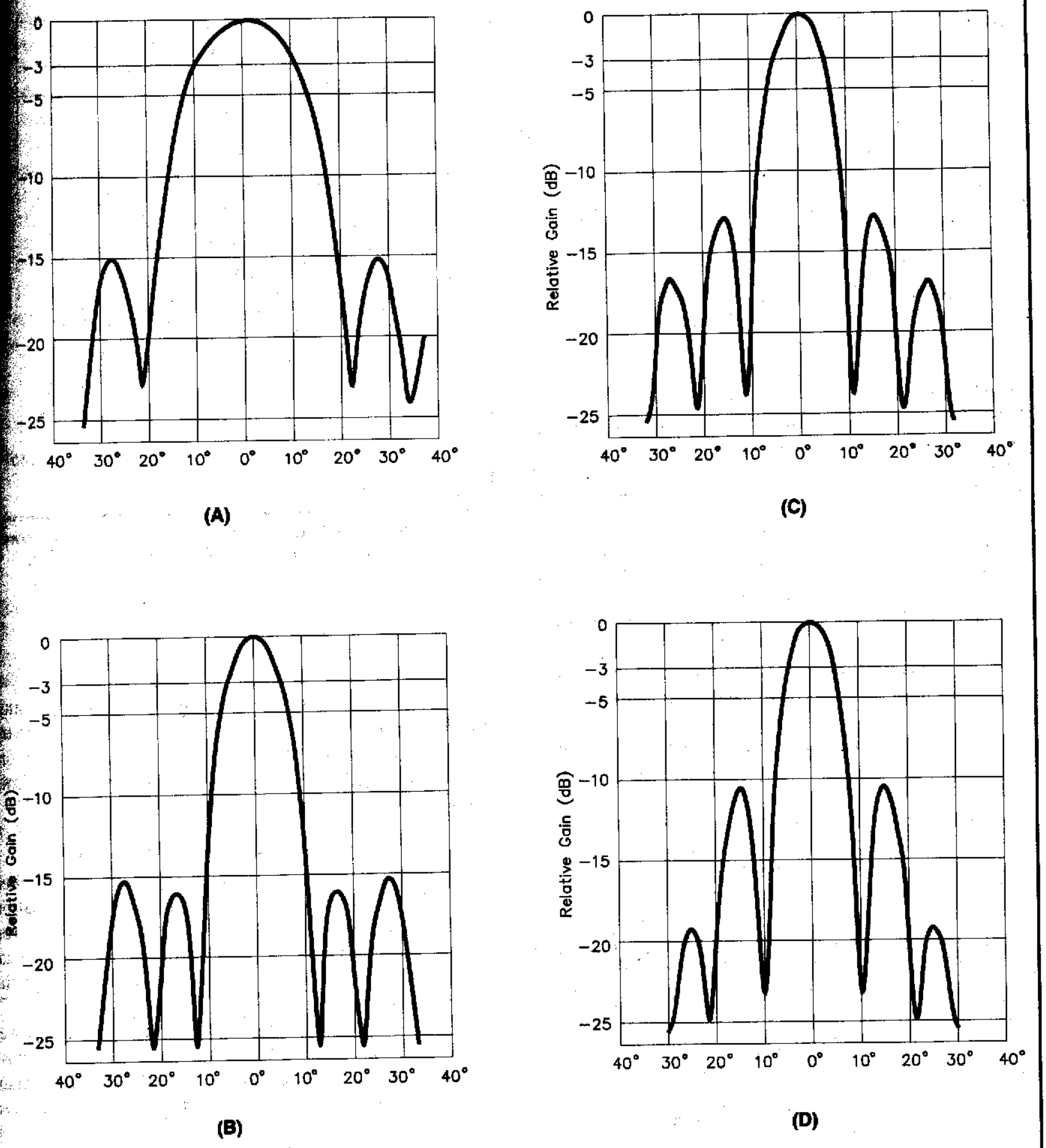


Fig 15—Stacking gain and sidelobe level versus normalized stacking distance (two antennas).



ig 16—Computer-generated H-plane pattern of a single, 22° half-power beamwidth Yagi (A). H-plane patterns are iven for pairs of similar Yagis stacked at 0.9 D_{opt} (B), D_{opt} (C) and 1.1 D_{opt} (D).

For example, the H-plane aperture angle of a 1296-MHz loop Yagi was measured to be 20°. From Eq 8, the optimum stacking distance (in wavelengths) is determined:

$$D_{opt} = \frac{\lambda}{2 \sin 10°} = 2.88\ \lambda$$

(The approximate formula $57\ \lambda\ /\ \phi$ would yield $2.85\ \lambda$.) The wavelength, λ, is

$$\frac{3 \times 10^8}{1.296 \times 10^9} = 0.2315\ \text{m}$$

So, D_{opt} would be about 0.666 meter, or 26.25 inches. Fig 15 shows stacking gain and first sidelobe level as a function of normalized stacking distance (with D_{opt} taken from Eq 8).

DJ9BV's calculated patterns for a single and two stacked Yagis at different spacings are shown in Fig 16 (A-D). One can see that significantly better sidelobe suppression can be obtained at a very small gain sacrifice by slightly understacking. For two antennas, a spacing of 0.9 to 0.95 D_{opt} looks like an excellent compromise in both the E and H planes—the benefits are independent of polarization.

Similar calculations were carried out for rows of three and four Yagis. They led to interesting findings:

- D_{opt} remains the same, regardless of the number of antennas stacked.
- The first sidelobe (and the second, in the case of 4 antennas) remains almost unchanged for large departures from D_{opt}.
- The best overall sidelobe suppression occurs at or slightly beyond D_{opt}; hence there is no case for understacking.

Practice has confirmed the above findings in most cases. Where larger differences were reported, they could usually be traced to the constituent Yagis—if they possess high sidelobe radiation, interaction can lead to grossly unequal power distribution. The best stacking results have always been reported with Yagis exhibiting low sidelobe radiation. This is particularly true for EME arrays where sidelobe noise pickup is a problem. Fig 17 shows the measured E-plane pattern of such an array, six K2RIW 19-element Yagis stacked two high and three wide, spaced in accordance with the above findings.

Power Distribution

All that has been said about stacking is based on the assumption of even power distribution, that is, equal power and phase at each antenna. This distribution will yield maximum array gain, usually of prime interest to amateur designers. To achieve this, the feed system must be laid out accordingly. Before proceeding, a word of caution is in order: *leave transforming-type feed lines to the "specialists."* Amateurs should use matched, low-SWR coaxial sections and high grade λ/4 transformers or combiners. At UHF and SHF, coaxial cable has enough loss

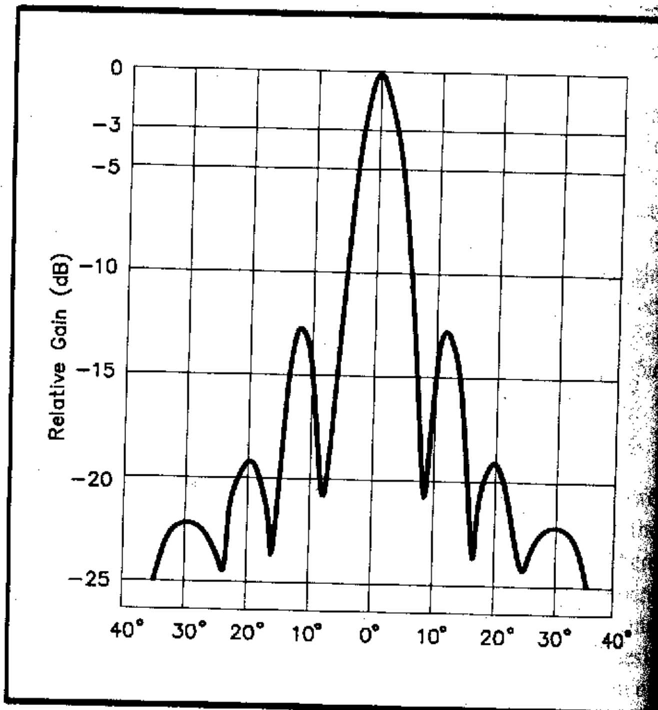


Fig 17—Measured E-plane pattern of six 25° half-pow beamwidth Yagis stacked two high and three wide, spaced 2.23 λ.

without putting standing waves on it. Cascading tra formers means cascading lossy distribution sections, so to obtain your gain with four or six *long* Yagis befo extending to eight or sixteen, which cannot be fed fro one distribution point.

Uneven Power Distribution

Any departure from an evenly spaced and exci array design will cause marked changes in the radiat pattern. There are so many possibilities of changing purpose or inadvertently) the power, phase or spa distribution that it is next to impossible to catalog consequences.

Only a few typical cases can be named here: po asymmetry will result in an asymmetrical pattern; ph asymmetry will cause squint (that is, a shifting of the m lobe away from boresight). A symmetrical, but une power distribution favoring the "outer" antennas produce increased sidelobe radiation and reduced g favoring the "inner" antennas results in reduced gain sidelobe radiation, along with a widening of the main l The latter can be desirable if low noise is the prime g The distortion arising from symmetrical, but uneven po distribution can be caused by coupling between adjac antennas, which is stronger on the inner sections of array. As a remedy for the distortion, a slight relocatio the inner Yagis could be tried. Interaction seems to be str est with Yagis having insufficient sidelobe suppression