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DEVELOPMENT AND EVALUATION OF THE 500 M GROUND-REFLECTION ANTENNA TEST RANGE OF THE CSIR, PRETORIA, SOUTH AFRICA

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ABSTRACT

This paper describes the development and evaluation of a general purpose ground-reflection antenna test range operated by the Council for Scientific and Industrial Research (CSIR). The range is 500 m long and the design is such to allow operation in the ground-reflection mode at L, S and X bands. The physical configuration of the range is presented to illustrate some of the practical problems experienced in implementing the range design. An experimental evaluation programme was conducted to determine the state of the incident field over the test aperture. Some of these results are presented to show the performance achieved with the range design.

1 INTRODUCTION

Ground-reflection antenna test ranges are designed to make use of the energy which is reflected from the range surface to create constructive interference with the energy from the direct path in the region of the test antenna. With proper design, the illuminating field will have small, essentially symmetric amplitude taper. The desired taper is obtained by controlling the range geometry and source antenna characteristics.

The CSIR has been operating an experimental station for satellite tracking and the launching of weather balloons at Paardefontein north of Pretoria since about 1963. When these programmes came to an end in about 1980, it was felt that the site would be ideal for the development of a general purpose antenna test range. This paper presents an overview of the design considerations, the implementation of the design and the evaluation of the range performance at L, S and X bands.

2 DESIGN CONSIDERATIONS

The ground-reflection antenna test range was designed in accordance with the procedures in reference [1]; not all the design considerations given there will be presented here but a few of the more important ones will be addressed.

2.1 Phase Curvature [1, pp 14-5 to 14-11]

The commonly employed far-field criterion which restricts the allowable phase variation over the test aperture D to 22,5 degrees gives the range length R as

$$R \geq \frac{2D^2}{\lambda} \tag{1}$$

At 3 GHz, with a 5 m aperture, this sets the range length at 500 m which can be accommodated at Paardefontein. The maximum aperture at 10 GHz is thus 2,74 m. Techniques of defocussing for paraboloidal antennas can be applied to increase the effective length of the test range [2],[3].

2.2 Amplitude Taper over the Test Aperture [1, pp 14-16 to 14-20]

The amplitude taper of the illuminating field along a horizontal line normal to the line of sight is determined almost entirely by the source antenna, the width of the test aperture and the range length. At 500 m, for a 5 m test aperture, only that part of the main beam between ±0,3° illuminates the test aperture. To achieve a 0,25 dB taper over the test aperture D the diameter d of the source antenna must satisfy [1, Eqn 14.24]:

$$d \leq 0{,}74\ D \tag{2}$$

For the range parameters given, this gives d(max) = 3,7 m.

The taper along a vertical line through the test aperture is almost independent of the source antenna pattern and is determined by the interference pattern between the direct signal and that reflected from the range surface. The height of the source antenna is adjusted to place the centre of the first fringe at the centre of the test aperture at a height h_r. For a given frequency with fixed range length R and test height h_r we have the following condition for the source height h_t [1, Eqn 14.31]:

$$h_t = \frac{\lambda R}{4h_r} \tag{3}$$

This value of h_t sets the maximum diameter d(max) for the source antenna since $d(\max) = 2h_t(\min)$.

With h_t as in Eqn 3, the normalised field strength is given by

$$E_N = \cos \frac{\pi}{2} \frac{x}{h_r} \tag{4}$$

where x is the displacement from the centre of the test aperture. For a 0,25 dB taper the height of the centre of the test aperture should satisfy the relation

$$h_r \geq 4\ D \tag{5}$$

For a 5 m aperture this requires a 20 m high receive tower. It was felt that this tower height would be impractical for a general purpose facility since it would require a crane and riggers to install even quite small antennas. As a compromise the receive tower height was set at 11 m to the centre of the elevation axis of the three-axis positioner. This gives a design taper for a 5 m aperture of about -0,6 dB. This will yield less accurate results than the more usual -0,25 dB taper but will be satisfactory for many applications. For more accurate results, the errors in gain and sidelobes produced by the -0,6 dB taper can be estimated [1, p 14-13]. With $h_r = 11$ m, the maximum source antenna diameter is 2,27 m which is considerably less than the 3,7 m given by Eqn 2.

2.3 Surface Smoothness [1, pp 14-37 to 14-40]

For effective operation in the ground-reflection mode, it is essential that the range surface be smooth enough to ensure specular reflection of the incident energy. This condition leads to the following "smoothness criterion" [1, Eqn 14.73]:

$$\Delta h \leq \frac{\lambda}{M \sin\psi} \tag{6}$$

where Δh is the root-mean-square deviation of the irregularities relative to the median surface, λ is the wavelength at the highest desired frequency, ψ is the grazing angle and M the smoothness factor. At the specular point we have [1, Eqn 14.74]:

$$\tan\psi = \frac{h_r + h_t}{R} \approx \sin\psi \qquad (7)$$

At 10 GHz with h_r = 11 m and h_t = 0,34 m (from Eqn 3) this gives ψ = 1,3° and Δh = 41 mm for a smoothness factor of 32 which corresponds to a very smooth surface. The specification for the range surface was set at a maximum peak deviation from the median surface of 25 mm, this will ensure effective operation at 10 GHz and will probably allow operation to 18 GHz in the ground-reflection mode.

3 THE MICROWAVE ANTENNA TEST RANGE

3.1 Physical Configuration

The antenna range which is shown in plan view in Figure 1, was designed as a 500 m ground-reflection range for L, S and X bands with the additional capability of an elevated range for X and Ku bands. The secondary range has a source-to-test antenna separation of 150 m and is set at right angles to the main range. The elevated range will use the same test equipment as the main range but it is not yet operational and will therefore not be discussed in this paper.

The primary range surface is compacted fill, graded to ±25 mm and covered with quick grass (*Cynodon dactylon*, also known as Bermuda grass) to maintain stability of the range surface. The grassed area is irrigated by a self-propelled water cannon sprinkler system. Suppression of wide angle scattering is achieved by the secondary cleared area which extends more than 100 m on each side of the range axis.

Prime power for the range is provided by the substation next to the entrance gates and a diesel generator serves as a back-up supply. Underground wiring ducts provide power, control and communications to the source tower from the range control building. The range control building is a single-storey structure oriented so that its sides make angles of about 45 degrees with the range axis. Range instrumentation is housed in an air-conditioned operations room.

The site at Paardefontein is situated in a high lightning incidence area; lightning researchers at the CSIR have estimated that there will probably be 12 major strikes over the next 20 years. Considerable care has been taken to provide low impedance earth rings around the control building and the source tower. All the range instrumentation is coupled to the low impedance earth. The base of the test positioner is tied to the earth ring via its three mounting bolts. A hand operated telescopic lightning mast can be winched into position very rapidly next to the antenna under test. During the early development of the range there were two lightning strikes which damaged the source tower and control room modems for the remote range controller. Drop-out relays were installed to protect the modems and intercoms during lightning activity which often occurs at night when power is switched off and no personnel are in attendance.

3.2 Source Positioning Equipment

The signal-source antenna is supported by a positioning system that provides polarisation rotation, azimuth and elevation pointing angle adjustment (squint) and height control. The source antenna is attached to the mounting flange of the polarisation positioner so that the antenna axis is concentric with the axis of polarisation rotation. The above functions and the source frequency are controlled remotely from the console in the operations room. Supporting the complete assembly is a carriage that moves on vertical rails to position the centre of the source antenna at any selectable height from about 0,3 m above ground level to about 11 m above ground level.

3.3 Test Positioning Equipment

A heavy duty three-axis (azimuth-over-elevation-over-azimuth) antenna positioner is mounted on the top of a 1,1 m diameter reinforced concrete tower which is independently mounted on a high strength footing. The tower has a 150 mm diameter central access hole for all control and receiver cables. A 0,6 m wide work platform with a removable safety rail is mounted about 2 m below the top of the antenna positioner. With the elevation axis at 0°, the horizontal face of the upper azimuth turntable is 11,2 m above ground. When the elevation axis is at 90° the upper azimuth acts as a roll or polarisation positioner with the centre of the turntable 11,0 m above ground. All the positioner functions are remotely controlled from the operations room console or can be operated from a local control on the roof of the control building.

3.4 Control Room Equipment

Operation of the range as a general purpose antenna measurement facility is conducted from the centralised console in the operations room. The console contains the receiver and ancillary equipment, such as the antenna pattern recorder, as well as the controls for the source and test positioner equipment. The status of the source equipment (frequency, height, polarisation and azimuth and elevation squints) is continuously available at the console via a remote range controller. The range is instrumented for operation in the frequency range from 500 MHz to 18 GHz. With special test set-ups VHF measurements down to 200 MHz can be accommodated on the range.

4 ANTENNA RANGE EVALUATION

Techniques for range evaluation are described in detail in reference [1] and the reader is referred there for a discussion of the procedures for incident field assessment. The measurements are made with a carriage-mounted probe antenna which is driven remotely along an I-beam support. The received signal is plotted automatically versus probe antenna position (total travel is 5,5 m (18 feet)).

Range evaluations have been conducted over a period of about a year starting with S band, then X band and finally L band. The results of some of the evaluations are presented below to illustrate the range performance.

4.1 S-Band Evaluation

The source antenna was a 1,83 m focused reflector and for these measurements a fairly high gain (17,8 dBi) probe antenna was used to reduce the need for absorber behind the probe antenna. Vertical amplitude patterns at 2,9 GHz are shown in Figures 2(a) and 2(b) as a function of source antenna height. The transmitter height which results in optimum pattern symmetry over the 5,5 m aperture is not quite the same for vertical (h_t = 1,06 m) and horizontal (h_t =1,00 m) polarisations. The taper across the aperture is about 0,6 dB. Taking the optimum height as 1,06 m we find that this is about 0,87 times the theoretical value of 1,176 m (from Eqn 3). The deviation in height is dependent on the soil conditions of the range and the measurement frequency. These observations are in agreement with the statements in reference [1, p 14-56] that the optimum height setting for horizontal polarisation is lower than that for vertical polarisation and that the nominal source height is about 0,9 times the theoretical value. Figures 2(c) and 2(d) show horizontal amplitude patterns as a function of source height. At each height the patterns are very similar as expected since they represent the azimuth beamwidth of the source and its image. The taper is about 0,4 dB in all cases over the full aperture. For the above measurements the range surface was dry.

In order to check the measured performance against the theoretical predictions, several vertical field probe cuts were taken on an expanded amplitude scale. Figure 3 shows the theoretical points, as calculated from Eqn 4, on the measured curves. For horizontal polarisation the measured amplitude taper is 0,5 dB while the predicted taper is 0,7 dB. The dip in the measured curve in Figure 3(a) at 2 ft down is caused by reflections from the probe carriage. This was readily demonstrated by placing microwave absorber behind the probe antenna. Figure 3(b) shows very good agreement between measured and predicted values at 2,9 GHz although there are small amplitude ripples (0,2 dB on the measured curve). Again it is felt that the ripples are not caused by the range surface but by reflections from the probe carriage which is parallel to the incident vertical polarisation. The ripples disappear when the frequency is changed as may be seen in Figure 3(c) for 3,9 GHz. Excellent agreement between theory and measurement is evident. The height of the source could not be reduced to obtain a peak at the centre of the probe since the source antenna rim would have been below the range surface. To achieve optimum performance at 3,9 GHz, a 1,22 m source antenna must be used. At the time of the measurements in Figure 3 the range surface was very wet, although there were no pools of water.

The measured polarisation characteristics of the field over the test aperture were relatively constant over the 5,5 m length of the probe support. Axial ratios better than 35 dB were observed for both vertical and horizontal incident polarisations when the probe antenna was moved through 5,5 m in both the vertical and horizontal planes. Damage to the synchro cable from the probe prevented measurement of off-principal plane cuts (±45° to the vertical).

The linearly polarised probe antenna was mounted to the upper azimuth positioner which then served as a polarisation positioner. With the elevation axis of the positioner at 91,26° the roll axis points at the range surface midway between the source and its image. Figure 4 shows a family of polarisation patterns taken with the source antenna vertical and then rotating the source in 22,5° steps to 90°. At the centre of the test aperture the axial ratio is 42 dB for vertical polarisation and 46 dB for horizontal polarisation. Away from the principal planes the axial ratio degrades reaching a value of 39 dB for the case of 45° incident polarisation. As the source antenna is rotated from vertical to horizontal polarisation the signal level increases by 0,3 dB for the polarisation matched condition. The cross-polarisation characteristics are far more sensitive to elevation squint of the source antenna than are the co-polarised field patterns shown in Figures 2 and 3. This probably results from the inherent off-axis depolarisation characteristics of the paraboloidal source antenna.

4.2 X-Band Evaluation

Aperture-field probe cuts similar to those for S band were made in X band. The source antenna for these measurements was a 0,61 m (2 foot) horn-fed reflector while the probe antenna was a nominal 22 dBi gain horn. Figure 5 shows the aperture-field patterns for 9,6 GHz measured when the range surface was dry. The optimum source heights for vertical and horizontal incident polarisations are identical (0,35 m) and correspond almost exactly to the theoretical height (0,355 m). The taper over the full 5,5 m aperture is 0,7 dB. As stated earlier, the far-zone criterion restricts the aperture diameter of X-band antennas under test to about 2,74 m (nine feet) for the 500 m range. Over this reduced aperture, the taper is about 0,3 dB for source heights between 0,34 m (probably down to 0,30 m) and 0,385 m which shows that the quality of the field over the test aperture is not too sensitive to fine adjustment of the source height. The patterns in Figure 5 are free of amplitude ripples (see particularly the expanded patterns in Figures 5(a) and 5(b)) showing that the specular reflection condition is well met in the ground-reflection mode. It has been found that when the range surface is very wet and the grass very long, the optimum source height exceeds the theoretical height by 50 mm or more [4]. Additional evaluations are required to establish the effects of soil moisture content on range performance.

Cross-polarisation measurements similar to those for S band were made over the 5,5 m aperture in the vertical and horizontal planes.

Figure 6 shows a cross-polarisation plot for the vertical plane on a 50 dB scale, the reference (0 dB level) pattern is for horizontal incident polarisation. The cross-polarisation level for horizontal incident polarisation is better than 35 dB over the full aperture while that for vertical polarisation is better than 40 dB. Similar results were achieved for the horizontal plane. As observed for the S-band measurements, the cross-polarisation characteristics are far more sensitive to elevation squint than are the co-polarised field patterns.

4.3 L-Band Evaluation

Since the range surface was found to give excellent performance in X band, it is almost certain the good performance will be maintained at all lower frequencies. This has already been demonstrated for S band where the optimum height was found to be 0,87 times the theoretical source height. The purpose of the L-band evaluation was to establish the factor by which the theoretical height should be multiplied to obtain the optimum height.

The source antenna was a 3 m (10 foot) dish fed by a broadband log-periodic-dipole antenna feed. Figure 7 shows the measured field distributions at 1,6 GHz using a 16,8 dBi probe antenna. Again excellent performance is achieved with the optimum height around 2,01 m. With the theoretical height of 2,131 m this gives a multiplicative factor of 0,94. At 1,2 GHz the optimum height was found to be 2,64 m compared to the theoretical height of 2,841 m which gives an adjustment factor of 0,93. No cross-polarisation measurements have been made in L band.

5 CONCLUSIONS

Aperture-field probe measurements indicate that the antenna test range at Paardefontein has excellent performance at L, S and X bands thereby fulfilling the requirement for a general purpose ground-reflection test range. As a rule of thumb the optimum source height is about 0,9 times the theoretical height at frequencies below about 3 GHz. At 9,6 GHz the optimum height is almost exactly equal to the theoretical height. Evaluations at X band have indicated that the soil moisture content can play a role in setting the optimum height particularly if the grass is long and there is water retention in the blades of grass.

More detailed evaluations are required to examine the off-principal plane cross-polarisation characteristics at the various frequencies of interest to establish error limits on polarisation measurements. As the requirements for higher precision measurements increase, there will have to be an ongoing programme of range evaluations. In particular, wide angle field assessments will have to be made to establish the signal levels arriving from angles far removed from the range axis.

6 ACKNOWLEDGEMENTS

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It is obvious that a project of this magnitude could not have been completed by the efforts of a single person. I thank the following people for their contributions: Prof John Cloete formerly of the CSIR, Messrs Searcy Hollis and Peter Evans of Scientific Atlanta, Mr Robert Ainslie the consulting engineer for the civil works, Mr Gary Lewis of Protea PNI (Pty) Ltd and Messrs Derek McNamara, Barend Taute and Bob van der Neut of the CSIR for their assistance in making the measurements.

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[2] R C Johnson, H A Ecker and J S Hollis : "Determination of Far-Field Antenna Patterns from Near-Field Measurements", Proc IEEE, Vol 61, pp 1668-1694, Dec 1973.

[3] D K Cheng and S T Moseley : "On-Axis Defocus Characteristics of the Paraboloidal Reflector", IRE Trans Antennas Propagat, Vol AP-3, pp 214-216, Oct 1955.

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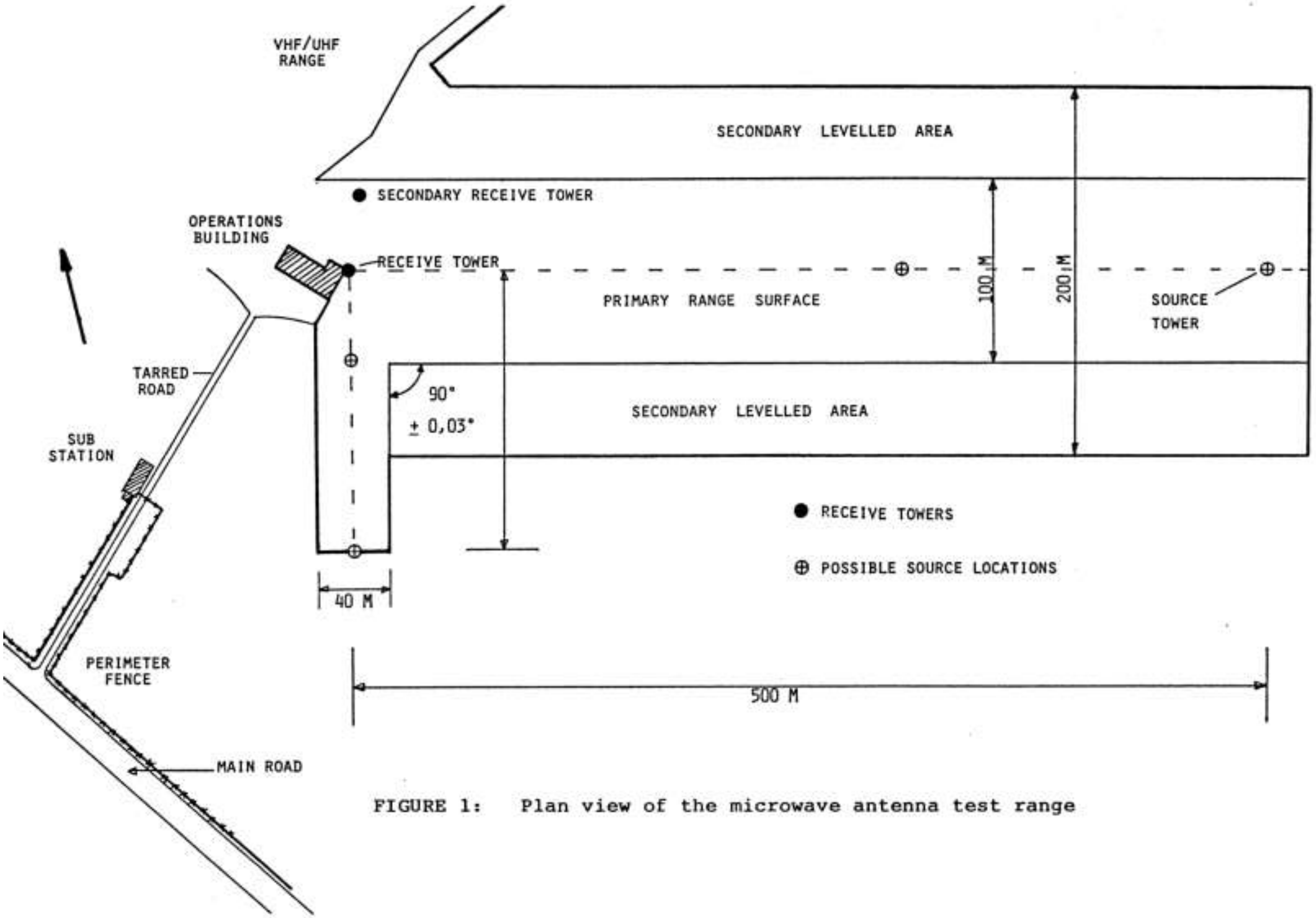
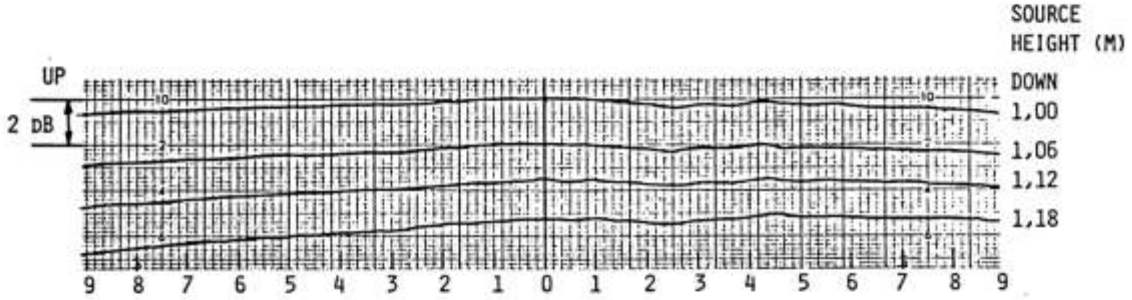
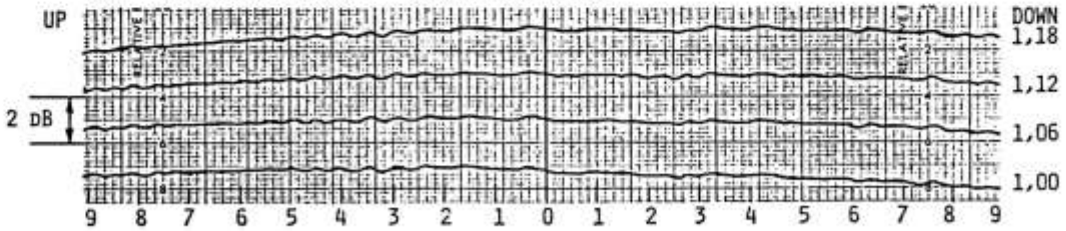


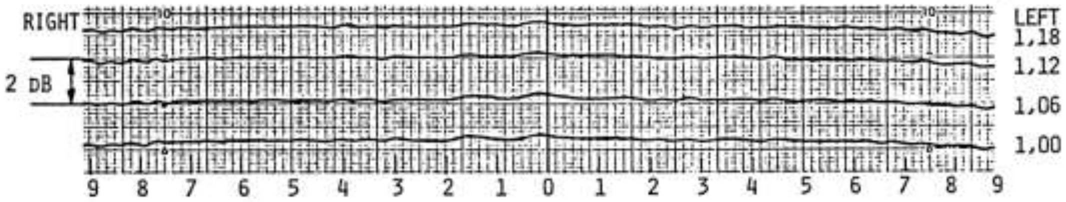
FIGURE 1: Plan view of the microwave antenna test range



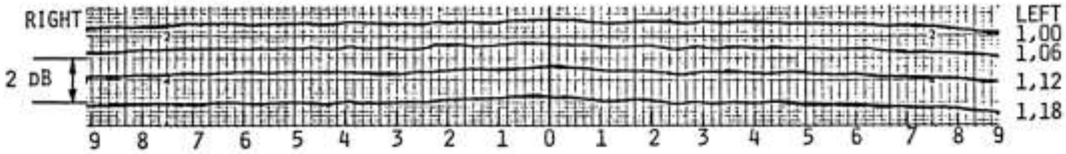
(A) VERTICAL PATTERNS - HOR. POLARISATION



(B) VERTICAL PATTERNS - VERT. POLARISATION



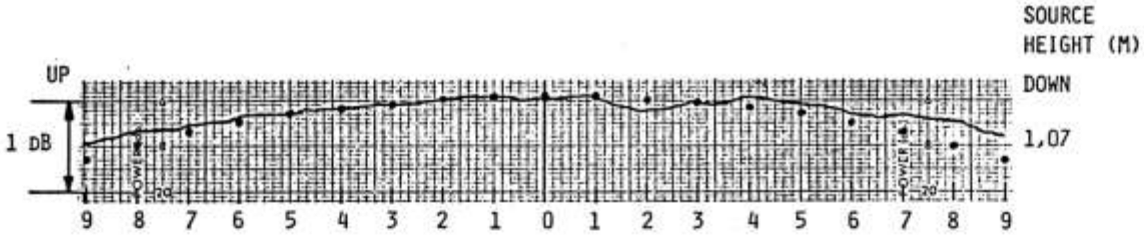
(C) HORIZONTAL PATTERNS - HOR. POLARISATION



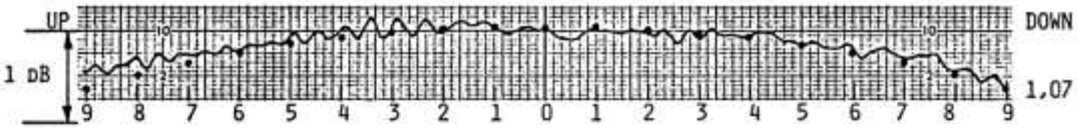
(D) HORIZONTAL PATTERNS - VERT. POLARISATION

DISTANCE FROM CENTRE OF APERTURE - FEET

FIGURE 2: Aperture field patterns for vertical and horizontal polarisations at 2,9 GHz



(A) VERTICAL PATTERN - HOR. POLARISATION F = 2,9 GHz



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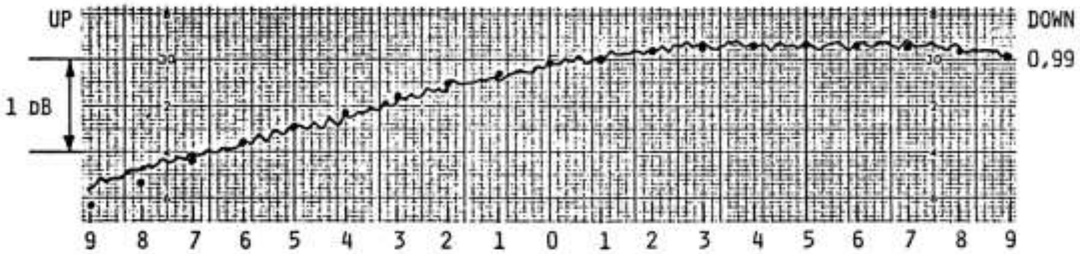


(C) VERTICAL PATTERN - VERT. POLARISATION F = 3,9 GHz

DISTANCE FROM CENTRE OF APERTURE - FEET

FIGURE 3: Vertical plane aperture field patterns showing predicted (• •) and measured (——) values

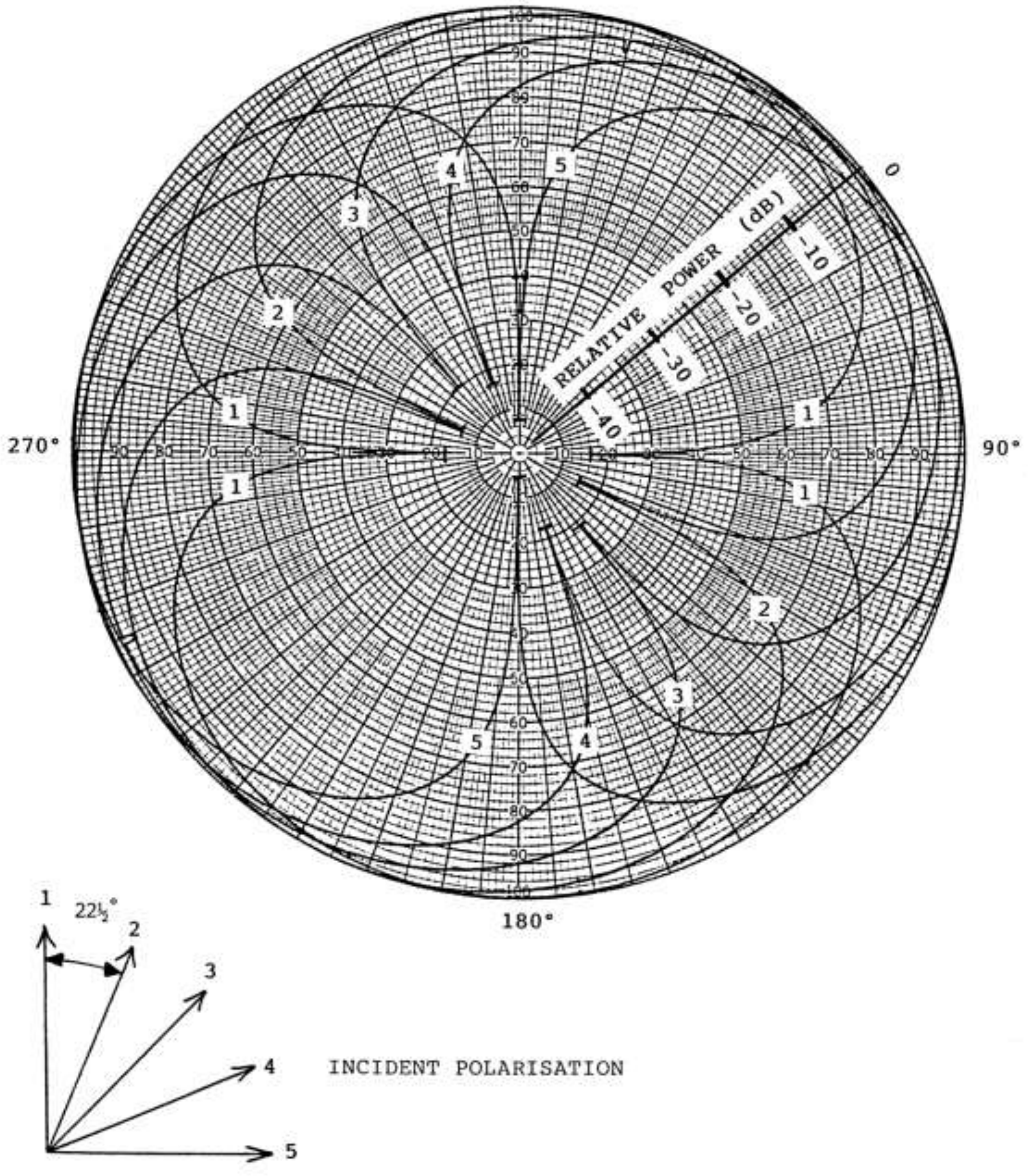
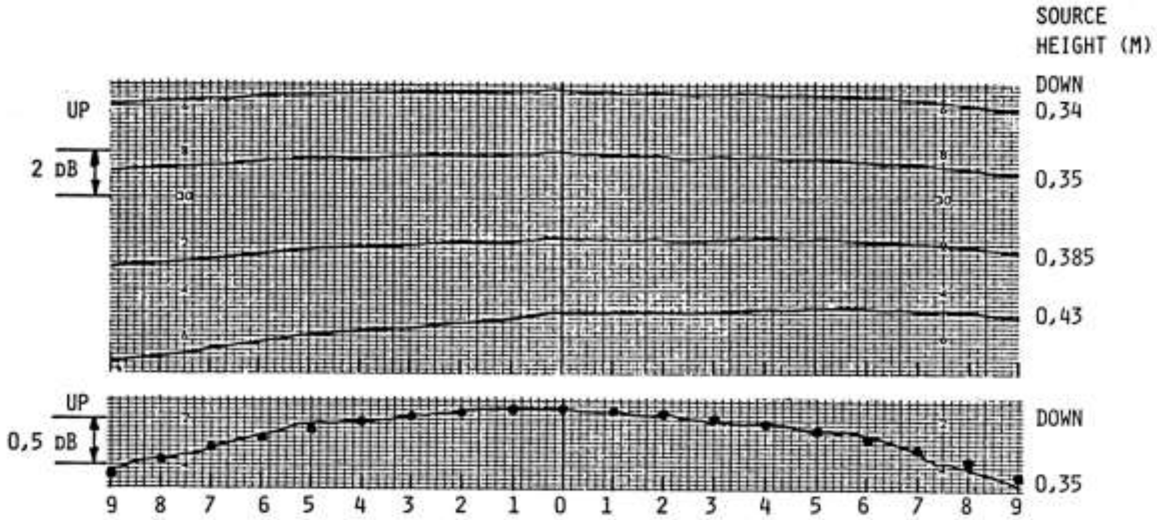
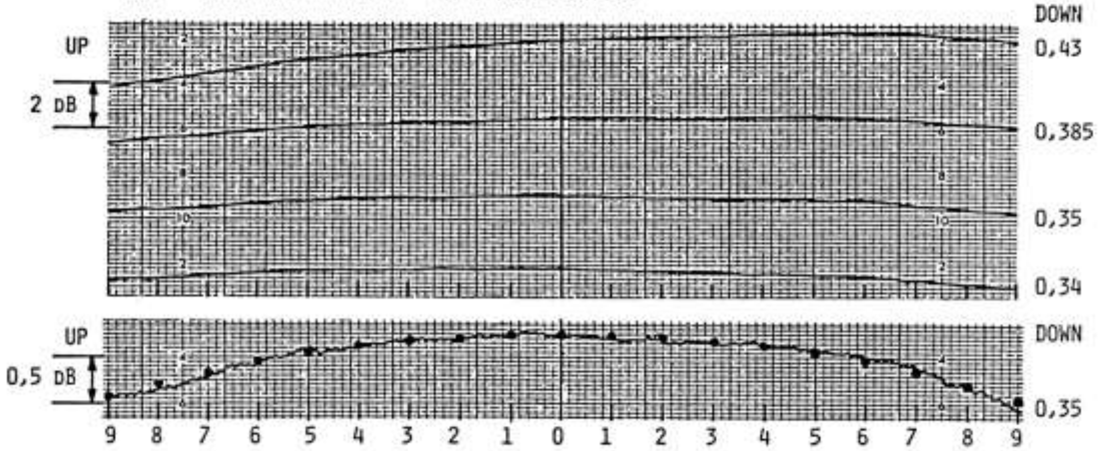


FIGURE 4: Family of polarisation patterns as a function of source polarisation angle at 2,9 GHz with h_t = 1,06 m

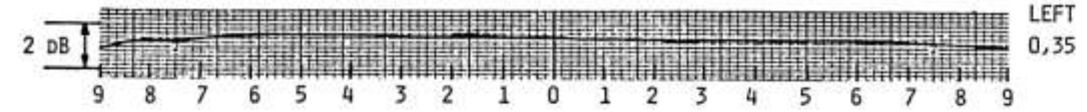


(A) VERTICAL PATTERNS - HOR. POLARISATION



(B) VERTICAL PATTERNS - VERT. POLARISATION

(C) HORIZONTAL PATTERN - HOR. POLARISATION



(D) HORIZONTAL PATTERN - VERT. POLARISATION

DISTANCE FROM CENTRE OF APERTURE - FEET

FIGURE 5: Aperture field patterns for vertical and horizontal polarisations including measured (———) and predicted (• •) curves at 9,6 GHz

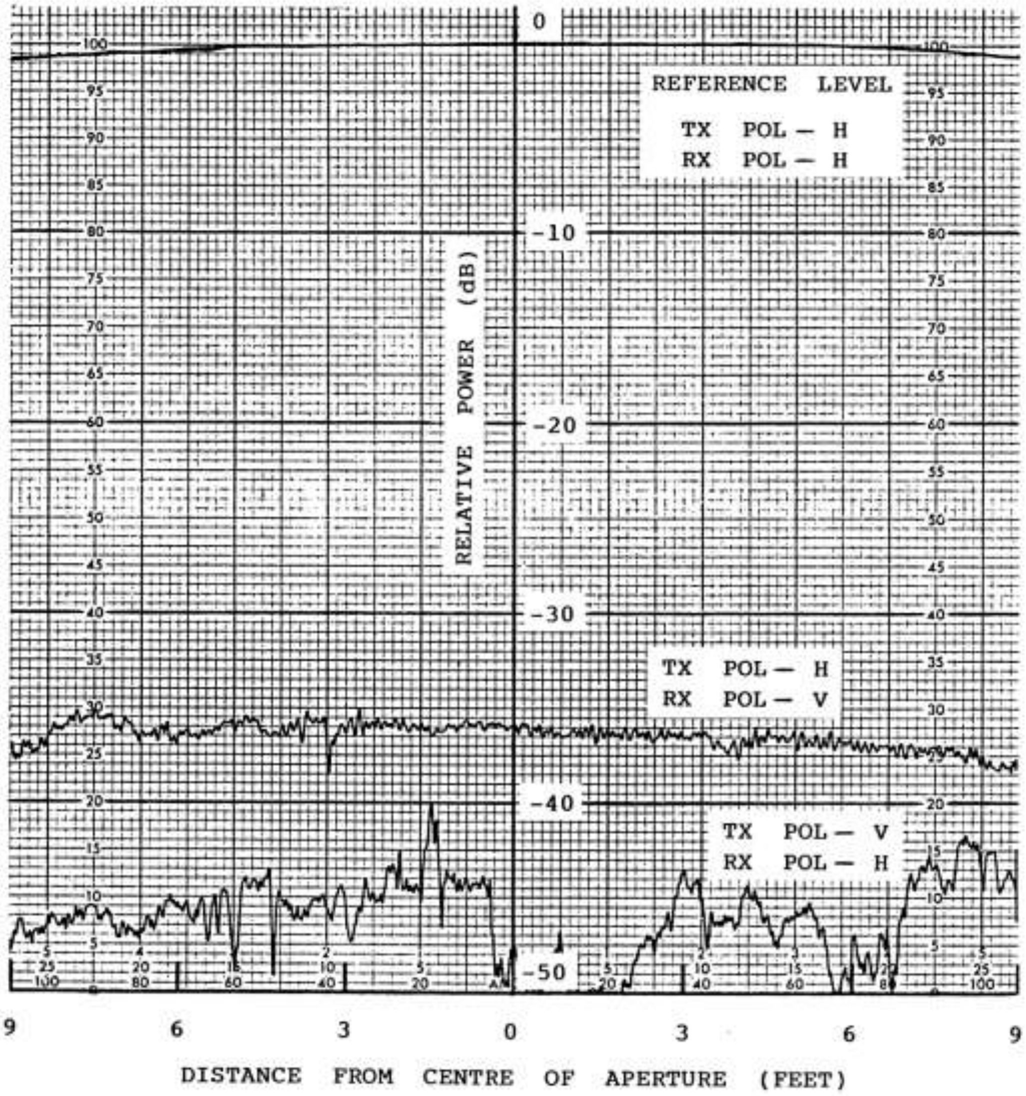
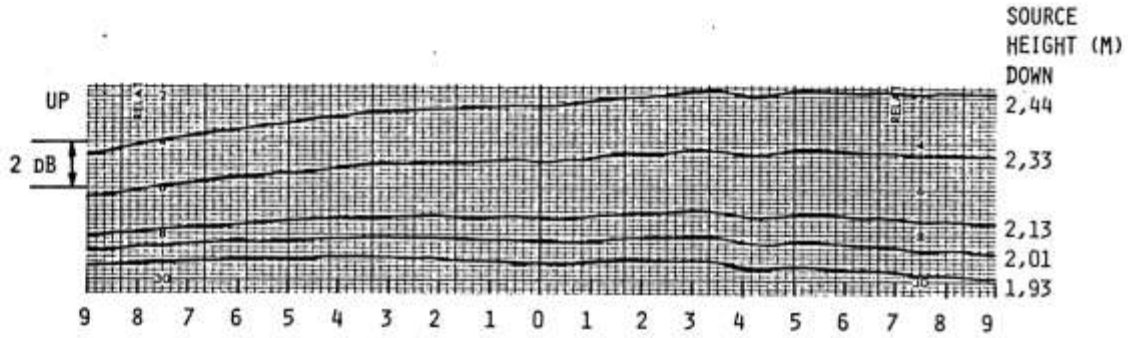
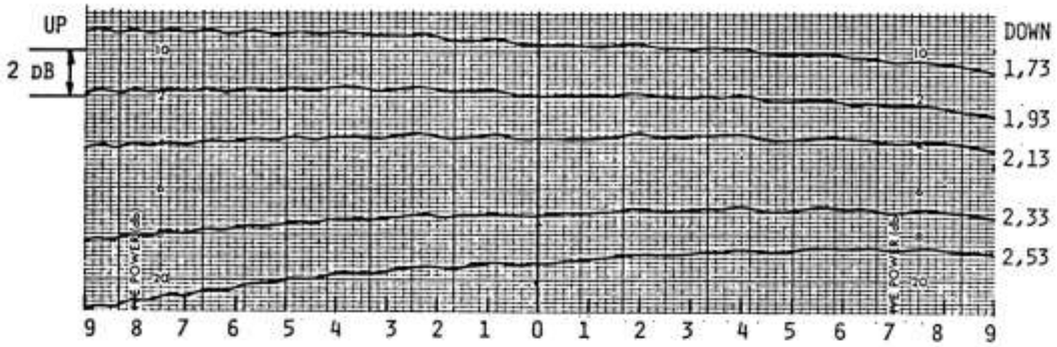


FIGURE 6: Cross polarisation level in the vertical plane over 5,5 m aperture at 9,6 GHz with h_t = 0,35 m

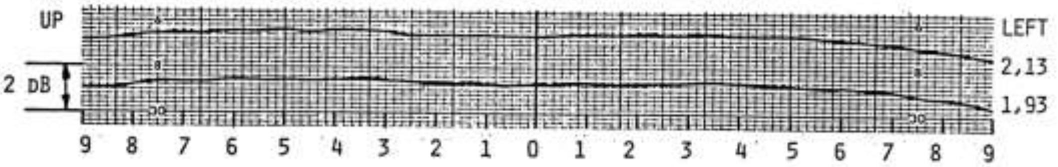


(A) VERTICAL PATTERNS - HOR. POLARISATION



(B) VERTICAL PATTERNS - VERT. POLARISATION

(C) HORIZONTAL PATTERNS - HOR. POLARISATION



(D) HORIZONTAL PATTERNS - VERT. POLARISATION

DISTANCE FROM CENTRE OF APERTURE - FEET

FIGURE 7: Aperture field patterns for vertical and horizontal polarisations at 1,6 GHz