Chapter 19B – ANTENNA RADIATION PATTERNS

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19B.0 INTRODUCTION

Modern civil and military aircraft are equipped with a variety of communication devices, radio navigation equipment, and air traffic control systems. For all of these devices appropriate antennas must be available to transmit and receive the signals. As a result, as many as 30 antennas, and sometimes even more, are mounted around today's aircraft. For this reason, it is necessary to know the capabilities of the receiving/transmitting equipment on board. These capabilities are driven by the antenna characteristics. Therefore, coverage, shading, and beam pointing pattern data are necessary for optimum electronic coverage. The aircraft antenna has to convert the available power density of the electromagnetic field to an electric voltage at its connector. This voltage level must be sufficiently high to operate the connected equipment. The reciprocity principle states that it makes no difference if the antenna is receiving or transmitting. For the certification of the aircraft antennas it must be proven that the antennas are at least generating the minimum receiver input voltage which is required for each radio service. The prime condition is, of course, that the specified field power densities of the different radio navigation and communication services are available.

An important property of a radio frequency link is the electro-magnetic field intensity at every point in space for a given output power of the antenna. As the propagation of radio frequency waves in free space is well known, the spatial distribution of the field intensity needs only be measured at one spatial sphere around the antenna. The information is usually given as distributions along the circumference of flat sections through this sphere: each of these is called an ARP. Several ARPs are usually required to describe the complete spatial antenna pattern of an antenna.

In addition to mathematical modeling, measurements on sub-scale models, and static measurements on full size models or aircraft on the ground, dynamic measurements on aircraft in flight play the most important role in the aircraft antenna testing and certification. [19B-1] The shape of an ARP, for one given frequency, is determined by the shape of the antenna and the shape and material of the surface it is mounted on. As the directly transmitted waves interfere with waves reflected by the aircraft skin with its complex geometry, and the surface material parameters are only roughly known, it is not possible to predict the ARP with the required accuracy. In ground measurements the earth's surface also acts as a reflector thereby causing the ground ARP to be different from the in-flight ARP. As the in-flight ARP is the ARP we are actually interested in it becomes clear that it is necessary to conduct in-flight ARP measurements.

The Flight Test Engineer must be aware of the needs of the specialists who are establishing the test program for measuring antenna patterns and radar cross sections. These tests will require special test equipment and dedicated flights to obtain the data that they require.

This Section provides an introduction to the principles of determining antenna patterns and the flight techniques for determining both antenna patterns and radar cross section. Reference 19B-1 provides detailed information.

19B.1 TEST OBJECTIVES

19B.1.1 Antenna Radiation Pattern

The objective of ARP tests is to determine whether reliable radio communication, and other electronic, links can be established in the required azimuth and elevation angles as seen from the aircraft. The following parameters play a role in this process: The output power of the transmitter; cable losses between the transmitter and the transmitting antenna; the gain and ARP of the transmitting antenna; attenuation in free space (which is dependent on the frequency and distance);the gain and ARP of the receiving antenna; cable losses between the receiving antenna and the receiver; and the sensitivity of the receiver. If, for any reason, the receiving antenna cannot supply the required input voltage to the receiver the communication link cannot be established.

For the usual radio navigation and communication systems the transmitter and receiver parameters and the resulting available electro-magnetic field power densities at a certain distance are known. The field power densities are specified in Reference 19B-2. The minimum required input voltage for each type of receiver is published in a series of ARINC publications. [19B-3, 19B-4, 19B-5, 19B-6, and 19B-7]

The available field power densities and the minimum value of the required receiver input voltages are listed in Table 19B-I which summarizes the requirements given in these references.

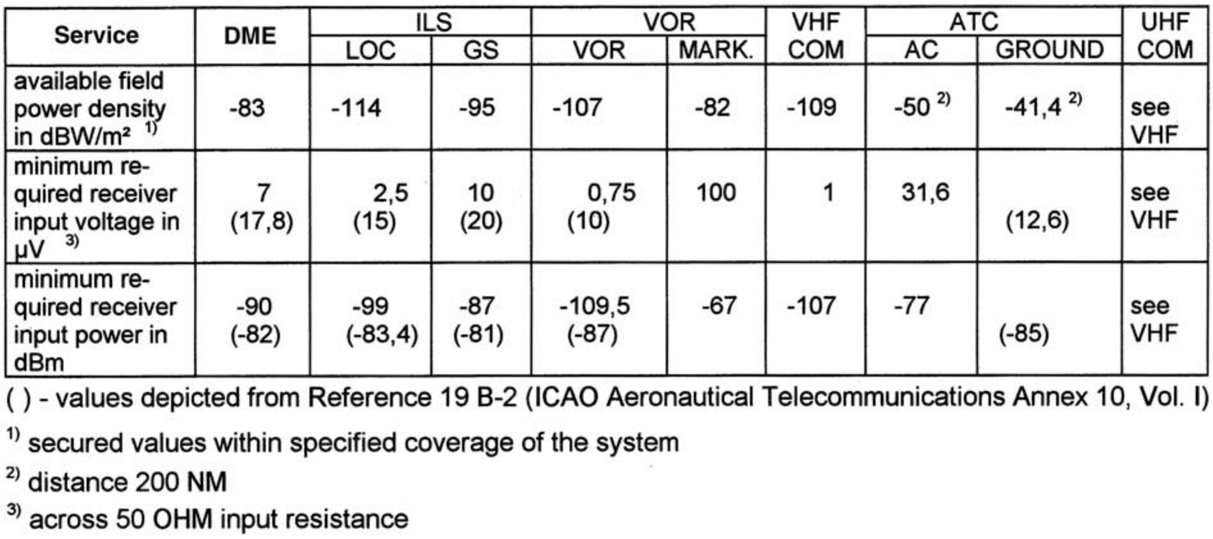
It has to be proven that each aircraft antenna is at least generating the minimum receiver input voltages given in Table 19B-I if the power densities listed there are available. This is determined by measuring the ARP within certain required angular coverage areas which depend on the radio system the antenna is serving.

19B.1.2 Lowest Required Power (LRP) Level

For each individual radiation pattern a lowest required power level (LRP) has to be calculated in order to assess whether the ARP is satisfactory. The lowest required power level (LRP) in the appropriate polar antenna pattern is a circle which is equal to the Maximum Power Level (MPL) of the antenna pattern under consideration minus the gain margin which is the difference between the actual gain of the receiver antenna (the antenna under test) and the minimal required gain of this antenna.

As described in detail in Appendix 19B.A the minimal required gain can be determined from the available power density, which is given in Table 19B-1. This table also gives the minimum required input power for the receiver. The actual gain of the receiver antenna can be calculated by utilizing the "gain-loss" equation given in Appendix 19B.A and reference 19B-1.

Table 19B-I Available Field Power Densities and Minimum Required Value of Receiver Input Voltage



Service	DME	ILS		VOR		VHF COM	ATC		UHF COM
		LOC	GS	VOR	MARK.		AC	GROUND	
available field power density in dBW/m² 1)	-83	-114	-95	-107	-82	-109	-50 2)	-41,4 2)	see VHF
minimum required receiver input voltage in µV 3)	7 (17,8)	2,5 (15)	10 (20)	0,75 (10)	100	1	31,6	(12,6)	see VHF
minimum required receiver input power in dBm	-90 (-82)	-99 (-83,4)	-87 (-81)	-109,5 (-87)	-67	-107	-77	(-85)	see VHF

( ) - values depicted from Reference 19 B-2 (ICAO Aeronautical Telecommunications Annex 10, Vol. I)

1) secured values within specified coverage of the system

2) distance 200 NM

3) across 50 OHM input resistance

An example of the determination of the LRP-circle in the radiation pattern of a glide slope antenna is given in Appendix 19B.A.

19B.2 MEASUREMENT REQUIREMENTS

19B.2.1 Aspect Angle and Coordinate Systems

The radiation direction of an aircraft antenna with respect to a receiving station (on the ground or in a second aircraft) is defined by the aspect angle Φ. This is the angle between the roll axis and the line of sight (Figure 19B.1). In order to cover the whole sphere, the aspect angle is resolved into two parts, the horizontal aspect angle Φ_A and the vertical aspect angle Φ_E. The horizontal aspect angle is measured in the yaw plane between the roll axis and the projection of the line of sight perpendicular to the yaw plane. The vertical aspect angle is the angle between the line of sight and its projection perpendicular to the yaw plane. In polar ARP plots one of these angles is usually taken as the independent variable, while radiated power is the dependent variable. For static measurements of models or full-sized aircraft, the aspect angle is readily obtained from the angle readouts of the pedestal. As will be shown later, in-flight measurements are more complex because the aspect angle depends on the relative locations of the ground station and the aircraft, as well as on the attitude of the aircraft.

Spherical coordinates for general use in antenna pattern measurements are defined by IEEE standards published in reference 19B-8.

In addition, the Inter-Range Instrumentation Group (IRIG) has published recommendations on how the orientation of an antenna-bearing vehicle should be described in the IEEE standardized system. [19B-9]

A detailed description of the orientation of aircraft to these systems in dynamic ARP measurements is found in Reference 19B-1. In this field of application it is common practice to denote the horizontal aspect angle by Φ_A, and to measure Φ_A from the nose of aircraft (positive roll axis) so that the right wing coincides with $\Phi_A = 90°$. The vertical aspect angle defined in Figure 19B-1 is usually denoted by Φ_E.

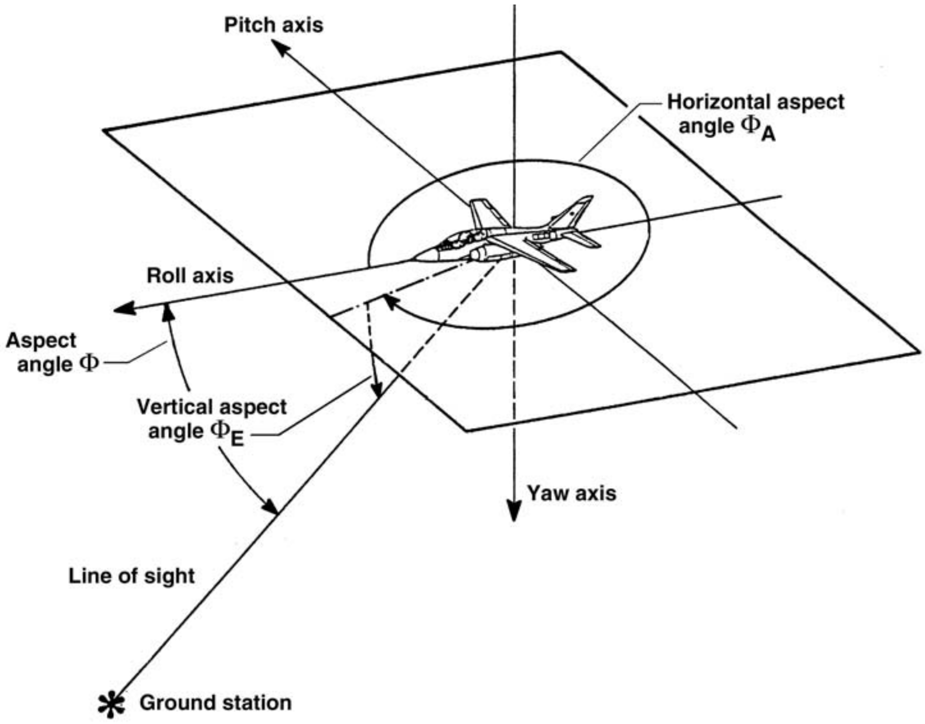


Figure 19B-1. Aspect Angle and Vehicle Coordinate System.

In order to achieve easy comparisons between dynamic and static measurements, the same coordinate system and notations should also be used for static measurements of models or full sized aircraft.

Aircraft antenna patterns are often presented in polar diagrams. Horizontal patterns are conveniently recorded by a continuous variation of the horizontal aspect angle while the vertical aspect angle Φ_E is stepped as a parameter. This leads to a movement of models under test on a cone, and the recorded patterns are conic section patterns. Due to the limited maneuverability of a full-sized aircraft in flight, conic section patterns cannot be measured during a complete continuous flight pattern. Nevertheless this type of mapping is frequently applied to model measurements.

The usual polar patterns for in-flight measurements are great circle patterns, which are recorded as the aircraft moves in a complete horizontal circle. If the circle is flown with different angles of roll, radiation patterns in the corresponding inclined planes through the aircraft roll axis are obtained. This means that the vertical aspect angle also changes and true parametric plots are thus not achieved.

A "matrix" plot in the form of a spherical surface projection provides radiation intensity at increments of Φ_A and Φ_E over the entire sphere. Radiation intensity appears as a plotted number in each element of the matrix or as contour lines of equal radiation intensity. The first representation allows only a rough angular resolution. The second one suffers from poor resolution of radiation intensity.

19B.2.2 Aspect Angle Determination

As mentioned in the preceding chapter the radiation direction of an aircraft antenna with respect to a receiving station is defined by the aspect angle illustrated in Figure 19B-1. To determine the aspect angle during tests, the following parameters have to be considered:

- Location of the ground station
- Location of the aircraft

- Attitude (pitch, roll and heading)of the aircraft
- Earth curvature

In a plane system, where the earth curvature is neglected, the aircraft and ground antennas are supposed to be at almost the same elevation and the pitch and roll angles of the aircraft are small, the determination of the horizontal aspect angle is very simple. As shown in Figure 19B-2, the horizontal aspect angle Φ_A becomes

$$\Phi_A = 180° - \beta_A + \Psi$$

if Ψ is the heading angle of the aircraft under test and β_A = 360° minus the azimuth angle of the aircraft as seen from the ground system. If the aircraft is tracked from the ground station, β_A can be measured directly. If no such tracking equipment is available at the ground station, β_A must be calculated from the outputs of radio navigation or inertial systems on board the aircraft. [19B-10]

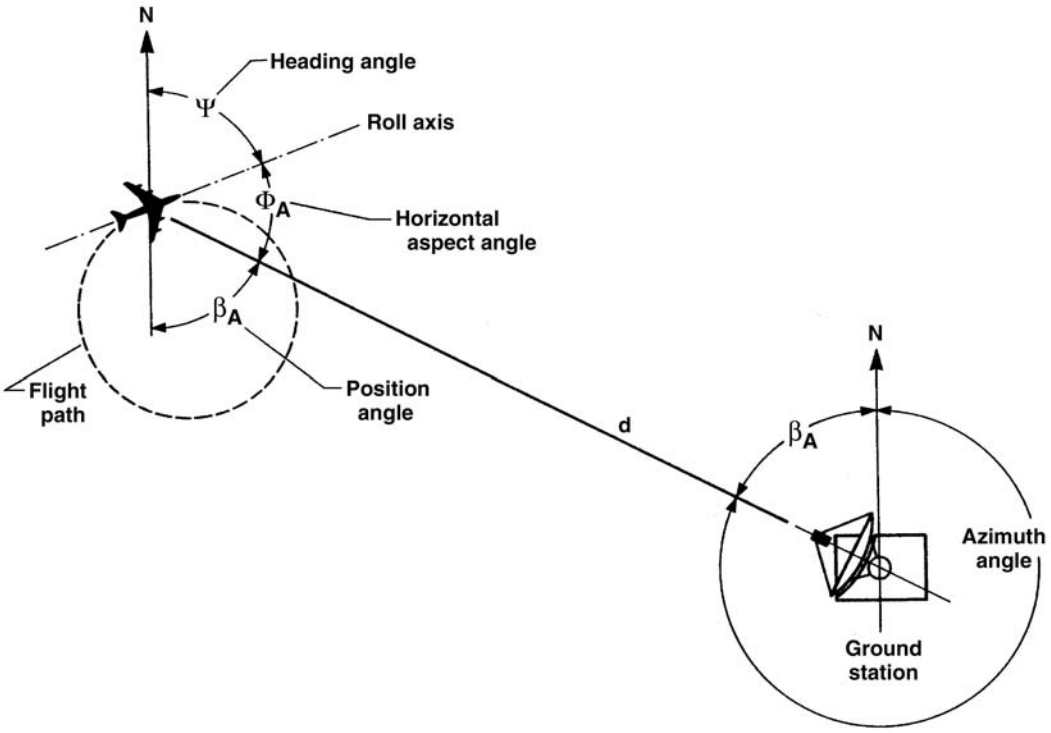


Figure 19B-2. Determination of the Horizontal Aspect Angle.

The determination of the vertical aspect angle Φ_E is very simple if the test flight is conducted in a vertical plane which also intersects the ground station (Figure 19B-3). The vertical aspect angle Φ_E then becomes

$$\Phi_E = \beta_E + \theta$$

where θ is the pitch angle of the aircraft. The position-dependent angle β_E equals the elevation tracking angle of the ground system. Again β_E can also be computed from available on-board information, derived from radio or inertial navigation equipment and altitude combined with distance measurement. [19B-10]

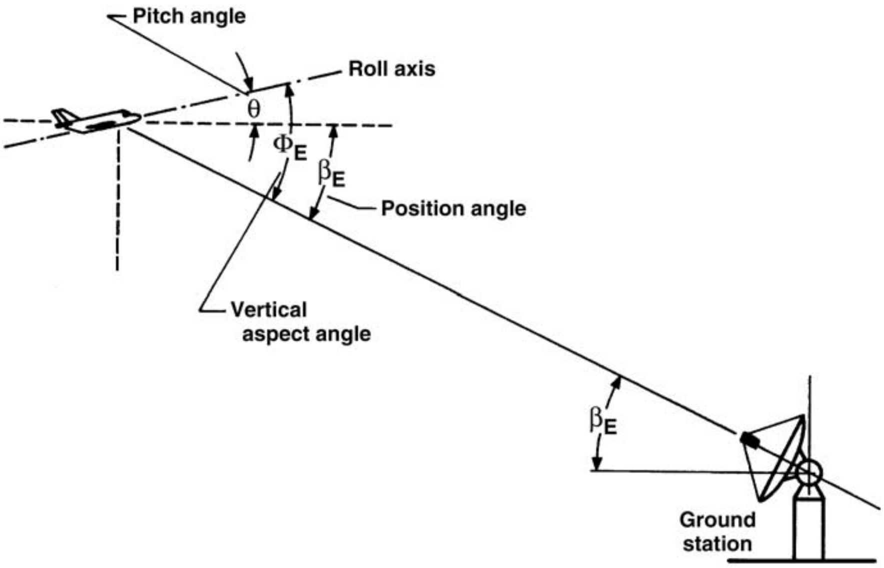


Figure 19B-3. Determination of the Vertical Aspect Angle.

If the above mentioned restrictions apply, the indicated equations are useful for the determination of the horizontal and vertical aspect angle. However, in many of the flight profiles discussed below, the horizontal and vertical position angle vary simultaneously. Also many flight profiles require changes of the angle of roll which influence the horizontal aspect angle.

A universal equation, which takes account of all parameters necessary to compute the two components of the aspect angle Φ_A and Φ_E in the general case, is given in Reference 19B-1.

In many applications the following simplified equation is used for on-line data processing and quick-look possibilities or to save computing time. [19B-1]

$$\Phi_A = \tan^{-1} (\tan (\Psi - \delta) \cos \Phi$$

where δ is the azimuth angle of the ground tracking system and Φ the bank (roll) angle of the aircraft.

19B.2.3 Distance Determination

Another important parameter in antenna measurements is the distance ***d*** of the antenna under test from the ground facility involved in the measurements. Distance variations during test flights cannot be helped if the antenna carrier is a fixed wing aircraft. In consequence the distance sensitive parameters have to be corrected. These parameters are the received power in the radio link (see gain-loss discussion in paragraph 19B.2.5) and the aspect angle, depending on which method is used for determination.

Direct measurements of the distance are possible by radar equipment or laser tracker devices. Other methods which make use of a telemetry data link are reported in reference 19B-11.

Indirect measurements utilize the outputs of inertial or radio frequency navigation equipment. The actual distance is then calculated by on-line computation if the geographical coordinates of the ground facility are known.

19B.2.4 Received Power Level for ARP

As mentioned above, the ARP is determined from the output signal of the receiver in the radio link set up for the test. Because the dynamic range of the received signal is large, the receiver must have a logarithmic characteristic, or an automatic gain control circuit. The ARP is usually recorded within a dynamic range of 40 dB. It is convenient to take advantage of, if possible, a receiver dynamic range of 60 to 80 dB. By this, adjustments of a pre-attenuater during measurements of patterns with unknown dynamic range can be avoided. Otherwise these adjustments are necessary to prevent overriding of the receiver. In order to record calibrated (absolute) patterns the receiver has to be calibrated over its total dynamic range prior to a series of pattern measurements.

As a consequence of the reciprocity theorem of antennas, the transmitting and receiving patterns of an antenna are the same. It, therefore, makes no difference whether the antenna under test is the transmitting or receiving antenna in the radio link set up for pattern measurements. Up to frequencies of several GHz the transmitter is usually smaller and weighs less than the receiver. Therefore it is convenient to mount the transmitter in the aircraft. At much higher frequencies the transmitting equipment becomes heavy and voluminous. Then the receiver is usually mounted in the aircraft, and either on-board pattern recording is used, or a telemetry system must transmit the measured signal to a ground processor, along with the other parameters necessary for the aspect angle calculation and distance correction.

19B.2.5 Propagation Problems

In a radio link set up for ARP measurements and characterized by the "gain-loss" equation presented in paragraph 19B.1.2, two parameters usually alter the recorded antenna signal and therefore have to be compensated by computation.

- The variation of the received signal due to a change of the distance r of the aircraft to the ground station has to be compensated by multiplying the losses by r^2
- The ground reflection multipath gain has to be considered.

The ground reflection multipath gain is investigated in more detail in reference 19B-1. If possible, distance, flight level, and receiving antenna height should be chosen such that the ground reflection multipath gain remains nearly constant during the test flight profile and only small corrections are necessary. The example outlined in Figure 19B.A-1 illustrates that a distance of more than 20 km is necessary for that application in order to cut off large multipath gain variations up to 20 dB. More examples which also illustrate the influence of soil wetness and sea water are given in reference 19B-1.

During vertical ARP measurements several deep attenuation nulls may be met in the course of a test flight (see paragraph 19B.4 and Figure 19B.A-1). At frequencies of about 1 GHz and higher a highly directive ground antenna can reduce this problem considerably. An alternative, also helpful at low frequencies, is to make use of the ground as a reflector for the receiving antenna. In order to obtain well-defined conditions, the surroundings of the ground antenna to a distance of several wavelengths are covered with a metallic mesh. This antenna arrangement has only one lobe, which covers the whole test flight, but corrections must be applied for the variations of gain within that lobe. The large distance variations during the test flight require additional corrections for the received power level.

In dynamic ARP measurements an important parameter is the range at which the measurements are made. Phase and amplitude variations over the illuminated test aperture have to be kept within certain limits in order to record correct ARP's. This is achieved by making the measurements in the "Far Zone". The accepted criterion as discussed in reference 19B-1 is

$$r \geq 2\,D^2/\lambda$$

with r = distance between on-board and ground antenna, D = maximum dimensions of the antennas and λ = wavelength. It is important to notice that the dimension of the on-board antenna can comprise the total aircraft due to possible reflections on parts of the metal structure. Compared to that the dimensions of the ground antenna are usually much smaller, e.g., the diameter of a parabolic dish at high test frequencies.

19B.3 THE DETERMINATION OF THE ARP BY STATIC METHODS

Section 19B basically deals with the flight test techniques for the purpose of aircraft ARP measurements. To be complete the other methods mainly applied in the early development stage of an aircraft are briefly covered here. More details on these methods can be found in reference 19B-1.

19B.3.1 The Determination of the ARP by Mathematical Modeling

Modern high-speed computers with large storage capacity have made possible the theoretical calculation of the ARP of antennas mounted on complex structures such as aircraft or helicopters. The main advantage of this mathematical method is that, once the shape of the vehicle has been represented in the computer, the influence of different positions of the individual antennas can be easily evaluated. If the position of an antenna has been selected on the basis of a computer evaluation, the number of measurements can be cut down to a minimum.

Disadvantages are that the shape of the vehicle can only be approximately modeled and that surface parameters such as conductivity and susceptibility are only roughly known. Therefore, the calculated results may contain errors and can only be considered as approximate patterns which usually have to be supplemented by full-scale measurements, either statically on ground ranges or by in-flight measurements.

Two different theoretical ARP-computation methods have been developed: the integral equation method and the geometrical theory of diffraction method. Which method must be used will depend on the size of the vehicle compared to the wavelength of the antenna under consideration. [19B-1]

19B.3.2 The Determination of ARP by Sub-Scale Model Measurements

In sub-scale modeling for determination of an ARP the device to be tested is scaled down in size to a ratio between 1:5 and 1:50, depending on the size of the original aircraft and the available measurement facilities. Modeling is usually done in two steps. First the antenna itself is scaled down, and its radiation characteristics measured and compared with the characteristics of the original full sized antenna. If, for this purpose, a counterpoise , e.g., a ground plane, is used the same scale factor has to be used. Thereafter the antenna model is integrated into the aircraft model and the ARPs are measured.

Sub-scale modeling has a number of advantages:

- The main advantage is the complete free mobility of the model in space, which allows a coverage of the whole sphere, so that true conic section or great circle patterns can be recorded
- Due to the small scale, measurements are frequently made indoors so that the effects of weather are eliminated
- Once a model has been manufactured, it can be used repeatedly for all kinds of antenna and radar cross section measurements, even if later additional antennas or structural modifications of the carrier are planned
- The small dimensions also allow reflecting walls or other obstacles to be screened by absorbing materials to create a clean electromagnetic environment for the measurements
- Model measurements do not require expensive aircraft flying hours and can be conducted by one or two persons.

The disadvantages of sub-scale model measurements are:

- A precision model must be manufactured. For high-frequency measurements the simulation of the cabin-roof, windows, and surface discontinuities, such as doors, access panels, etc., is especially difficult.
- The model laws can not be performed completely. Measurements conducted in free space do not require transformation of the permeability and permittivity, but frequency and conductivity have to be increased by the factor of reduction. The frequency requirement can be fulfilled in most cases, whereas the conductivity requirement is usually violated.
- Sub scaling of the antenna elements requires much experience about where a certain degree of definition can be neglected and where not.

19B.3.3 The Determination of ARP of Full Size Aircraft on the Ground

Military aircraft often fly in several configurations with different weapon systems, ECM pods, or fuel tanks at different store points below the wings or fuselage. The effect of the different configurations on antenna radiation patterns must be investigated. If all these patterns were measured in flight, it would require a large number of expensive flying hours. To avoid this, static ARP tests can be executed on full-scale airframes, mockups or airframe sections mounted atop heavy 3-axis positioners on outdoor antenna test ranges.

The advantages of this method are:

- Measurements are made on full-scale aircraft, no constraints due to model laws have to be considered and no up-translation of frequency is necessary. All measurements are made at the correct frequencies.
- The "test aircraft" need not be fully equipped, especially inside the airframe. In many cases a mock-up is adequate and modifications in the configuration can be realized by makeshift or temporary arrangements in which only the radio frequency aspects need be taken into account. This, in conjunction with the saving of many flying hours, speeds up the measurements and increases the economy of ARP recording.
- Since the aircraft can be inverted, antenna-to-antenna isolation measurements of two or more antennas mounted on the same airframe can be made without the influence of ground-coupling on antennas below the fuselage and wings.

The following disadvantages have to be considered:

- Due to the large weight of the airframes under test, the pedestals have to be rugged enough to carry up to 25 tons
- The large dimensions of the device under test require a large quiet zone for the illuminating field which leads to high towers and - in conjunction with the far-field condition requirements - to very large test areas
- If reflections of the illuminating RF-signals by ground and other obstacles are present, additional measures must be taken to attain the desired accuracy of the measurements.

19B.4 THE DETERMINATION OF ARP OF FULL-SIZE AIRCRAFT IN FLIGHT

During in-flight measurements of ARP the aircraft antenna under test is part of an air-to-ground radio link. The aircraft flies selected maneuvers in front of the ground antenna, whereby the following parameters are recorded:

- If the transmitter is on board the aircraft, the transmitted power, if the receiver is on board, the received power
- The (transmitted or received) power at the ground station
- The position of the aircraft relative to the ground station
- The attitude angles of the aircraft.

The gain of the aircraft antenna must then be calculated from the "gain-loss" considerations noted in paragraph 19B.1.2 and Appendix 19B.A. The flight trajectory for these tests must be chosen carefully to ensure that the other parameters in the equation remain as constant as possible and can be calculated with the maximum accuracy. The optimum trajectories are discussed later on in this chapter.

The advantage of this method is that the antenna gain is measured under actual conditions, without any errors due to modeling imperfections. The effect of moving parts, such as propellers, helicopter rotors and stabilizing rotors is fully taken into account. Measurements of this kind are necessary for the certification of new aircraft types, even if model calculations and model measurements have been carried out.

The main disadvantage of this method is the high cost of the flying hours that are required. For that reason the flight tests usually are the final stage of a long process of static testing. Problems of in-flight measurements are:

- The flight characteristics of the aircraft limit the choice of aspect angles (see paragraph 19B 2.2) at which measurements can be made
- The effect of ground reflections may vary considerably during the flight tests and it is difficult to eliminate these effects (however, with proper processing, these effects can be eliminated from the ARP especially if all reflections occur over water or reflecting ranges)
- Delays due to weather conditions and aircraft availability
- Increased processing requirements to remove the dynamic perturbations and range tracking errors.

The effects of many of these disadvantages can be reduced by careful planning of the trajectories flown during the tests, as described below.

When measuring an ARP it is not usually necessary to cover the whole sphere above and below the antenna under test. The aspect angle zone of interest depends very much on the maneuverability of the aircraft and on the kind of radio aid under consideration. Once the angular range to be covered by the measurements is defined, the flight profiles can be selected. Continuous flight trajectories which allow complete continuous radiation pattern recordings are very efficient with respect to flying time and data processing. Unfortunately, certain angular areas of the sphere cannot be covered by continuous flight trajectories, and measuring requirements may call for additional discontinuous flight trajectories, e.g., straight trajectories, usually with constant attitude and altitude (Figure 19B-4).

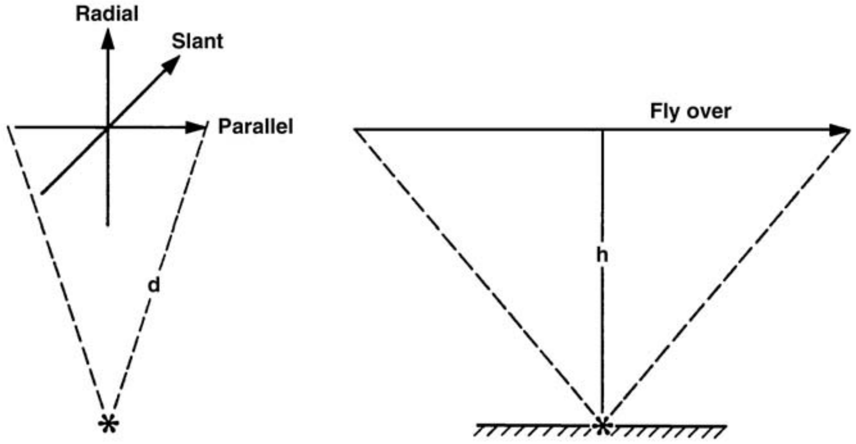


Figure 19B-4. Straight Flight Test Trajectories for ARP Measurement, d = Distance; h = Altitude.

While radial, slant, and parallel flights are suitable and qualified for horizontal antenna pattern measurements, the fly-over trajectory is better suited to vertical antenna patterns, at least for those below the fuselage of the aircraft. Refer to Figures 19B-5 and 19B-6.

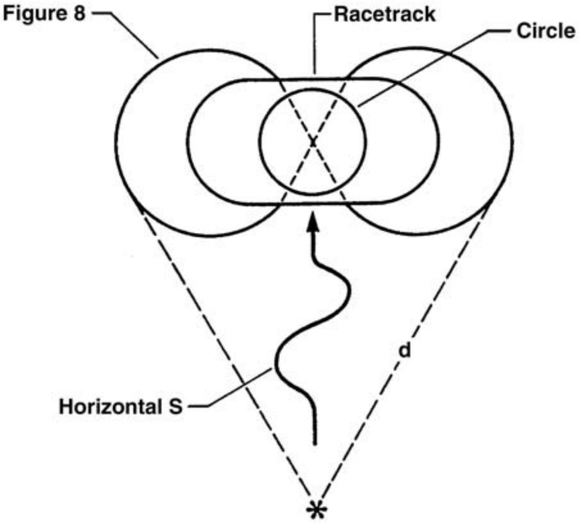


Figure 19B-5. Curved Flight Test Trajectories for ARP Measurement, Fixed Altitude d = Distance.

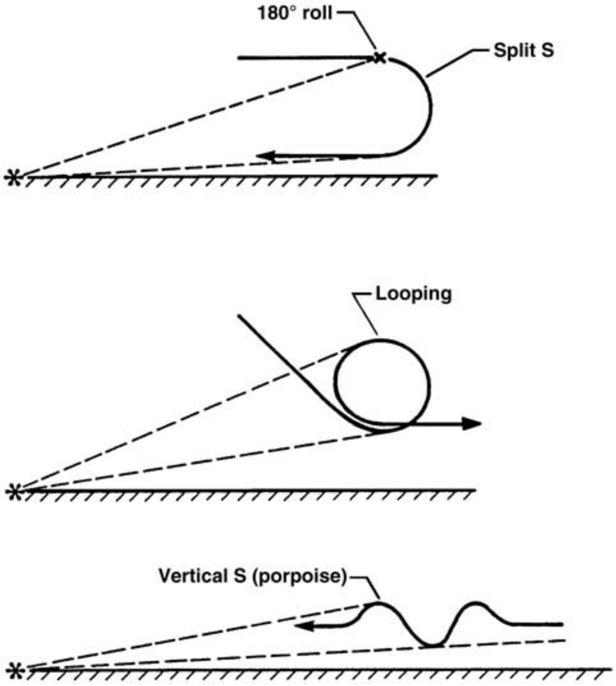


Figure 19B-6. Curved Flight Test Trajectories for ARP Measurement, Variable Altitude.

Curved flight test trajectories for ARP measurement, usually flown at a fixed altitude, are shown in Figure 19B-5. The circle or orbit trajectory is very easy to fly, the aircraft circles in a skidding turn or at a constant bank angle, each turn covering a complete 360-degree great circle antenna radiation pattern. Therefore this trajectory is one of the most efficient profiles for ARP measurements as far as flight time is concerned. In a flight at great distance and at low altitude, the coverage of the depression angle in the nose and tail area of the aircraft is poor. The coverage of the depression angle can be improved by flying the aircraft at higher altitudes. The race track trajectory, very similar to the circle pattern, allows a gyro realignment during the straight course runs connecting the semicircles. The figure eight trajectory of Figure 19B-5 allows the aircraft to fly left- and right-hand turns during the same maneuver. In the dashed section of this figure no measurements are recommended because the roll rate of the aircraft is very high. To complete a 360-degree antenna pattern, the maneuver has to be repeated under conditions where the figure eight is turned 90 degrees with respect to the ground station. If only the nose and tail horizontal patterns of an aircraft antenna need to be measured, the horizontal "S" flight trajectory is convenient. Also, descents pointing at the ground station and climbs away from the ground station are useful for getting nose-on and tail-on data.

The candidate curved flight trajectories for ARP measurements in the vertical plane are shown in Figure 19B-6. For a split S trajectory the aircraft starts from straight horizontal flight, then performs a 180-degree roll and finally reverses its flight direction diving to a lower flight level. This maneuver gives nearly 180 degrees of coverage of the nose-tail elevation cut but can be performed only by highly agile aircraft. The looping trajectory, where the aircraft performs a 360-degree vertical turn, extends the coverage to a complete 360-degree vertical radiation pattern. The vertical "S" or porpoise trajectory, during which the aircraft alternately dives and climbs, gives a limited coverage of the depression angle in the nose and tail area. If the distance is large it can even provide data on small negative depression angles.

In many cases a combination of the previously mentioned trajectories is used to achieve a rational and economic flight test program.

19B.5 DATA ANALYSIS

From the above mentioned requirements for the determination of aircraft antenna patterns, a listing of required parameters can be generated. Table 19B-II provides a list of parameters required for ARP determination. As this list indicates, there are generally two locations of data sources, one on-board the aircraft and one on the ground.

Table 19B-II Parameters Required for ARP Determination

	Parameter	Sensor	Tolerance Error
On-Board			
	Roll Angle	Inertial Reference System	< 1 degree
	Pitch Angle	Inertial Reference System	< 1 degree
	Heading Angle	Inertial Reference System	< 1 degree
	Altitude	Air Data Computer	100 m
	Present Position/ Longitude, Latitude	Radio Navigation/ Inertial Navigation	100 m
	Field Intensity	Special Equipment	1 to 3 dB
Ground			
	Azimuth Angle	Tracking System	< 1 degree
	Elevation Angle	Telemetry/Radar	< 1 degree
	Distance	Telemetry/Radar/(On-Board Navigation System)	100 to 200m
	Field Intensity	Special Equipment	1 to 3 dB

For data computation and analysis it is important that all parameters are available at a computing facility at the same time. There are three ways to accomplish this. If the data processing takes place on board, the ground data has to be transmitted on-line to the device under test. If the data processing facility is on the ground, a down link is necessary for data transmission. Both methods allow on-line data processing and analysis. A third method is to record on-board and ground data separately in conjunction with time signals and let the computing system synchronize the two data streams in a post-flight analysis. The main disadvantage of this method is that no quick-look analysis is possible during the flight tests.

The data processing facility must compute the aspect angle and make the necessary corrections of the measured field strength due to variable distances, ground reflections and ground antenna characteristics. The computed data thereafter has to be processed for pattern recording, e.g., for the presentation of polar patterns.

In this processing process it is important to pay attention to the sampling theorem. In this case it means that a minimum of 5 sets of data points have to be calculated to display one lobe of the pattern. At high frequencies, in the order of 5 GHz, one pattern lobe may be observed in a 1-degree aspect angle area. A turn rate of 3 degrees per second therefore requires 15 complete calculated data sets on-line processing presumed. At this turn rate and a 60-degree banked turn the speed of the aircraft under test must be 600 knots (see Figure 19B-7). This figure illustrates that angle and speed must be carefully adjusted to an acceptable turn rate of the aircraft under test. Another dependent parameter also given in Figure 19B-7 is the turn radius, which causes distance and field strength variations.

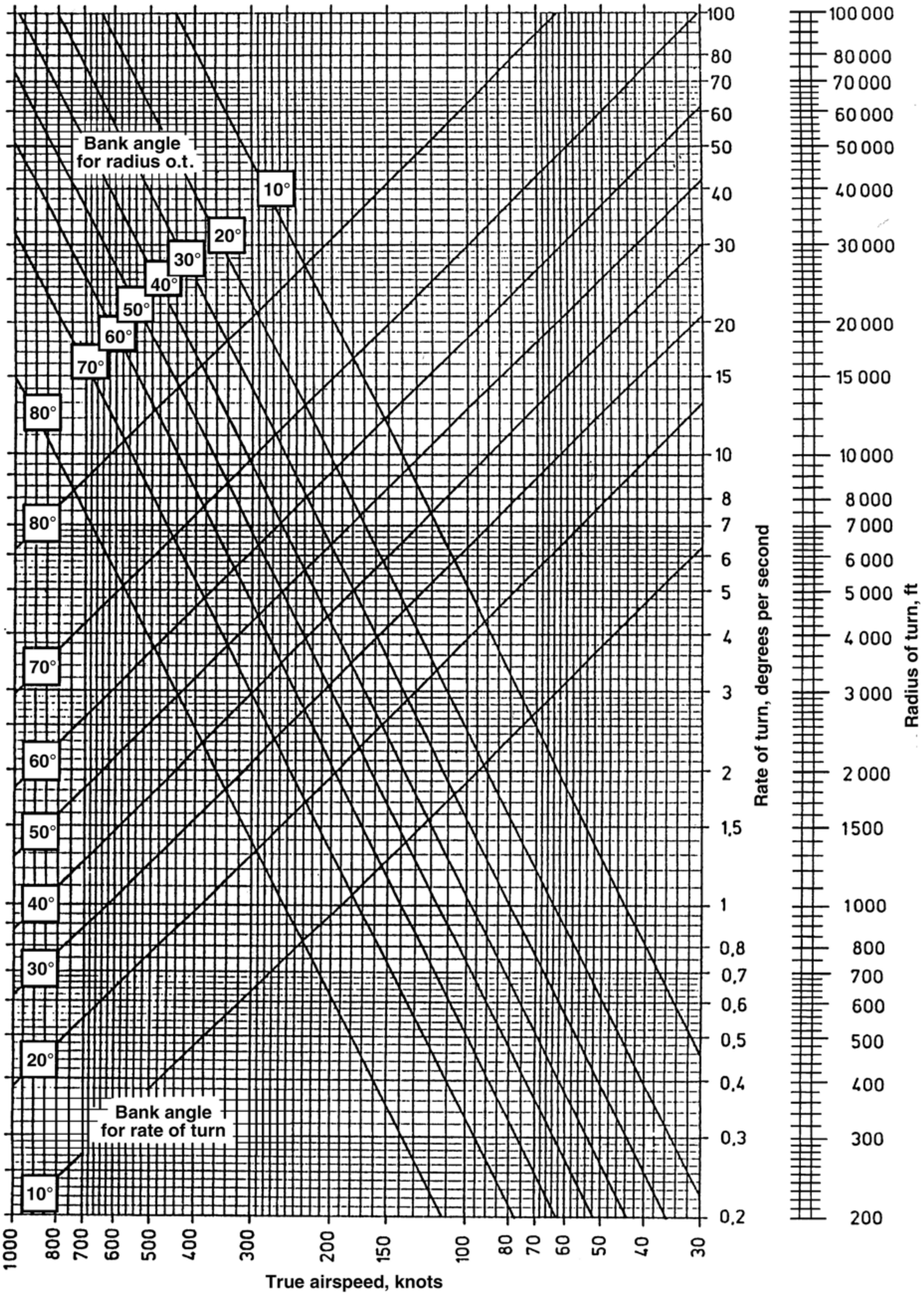


Figure 19B-7. True Airspeed with Respect to Rate and Radius of Turn, Bank Angle as a Parameter.

19B.6 DYNAMIC RADAR CROSS SECTION (RCS) MEASUREMENTS

A brief overview of radar reflectivity measurements generally conducted in anechoic chambers and outdoor test ranges is given in Section 19A.

The determination of RCS of real aircraft in flight is treated here because from a flight test point of view there is a great similarity in procedures and methods for dynamic RCS measurements and the described ARP measurements. The major advantage of such dynamic RCS measurements is that data is obtained in the normal operating environment of an aircraft. All target details and effects of target motion are included. For the RCS measurement system, the antenna radio link receiver must be replaced by the receiver of the test radar. For this the automatic gain control (AGC) output voltage or the intermediate frequency (IF) output signal of the radar receiver has to be adapted to the data acquisition system. Generally, this signal has a poor long-term stability. Therefore, just before or after the measurements the characteristic of the receiver output voltage has to be calibrated to the RCS. This is usually done by launching a balloon carrying a sphere with well known RCS being completely independent from the angle of incidence. This sphere is tracked by the radar and the distance variation serves for a complete sweep of the receiver output voltage down to the noise level. More information on system considerations and examples of existing measurement facilities are given in Reference 19B-1. Appendix 19B.B includes some results of dynamic RCS measurements.

19B.7 CONCLUDING REMARKS

In this Section the need, requirements, methods, and test techniques for dynamic in-flight measurements of aircraft antenna radiation patterns have been outlined. It has been shown that the application of modern data acquisition and processing systems, in conjunction with telemetry, can speed up the expensive flight tests considerably. However, problems in connection with wave propagation in the radio frequency link have to be considered carefully in order to avoid incorrect measurements. Various flight profiles and their advantages and disadvantages have been discussed.

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APPENDIX 19B.A – LRP DETERMINATION OF A GLIDE SLOPE ANTENNA

The determination of the lowest required power level LRP in a measured antenna pattern is discussed in paragraph 19B.1.2. In the following example a glide slope antenna is examined. The utilized gain-loss equation is derived in reference 19B-1. The term 32.54 includes all constant factors within this equation and the dimension constants. It is also mentioned that the power given in dBW is referenced to 1 Watt and in dBm to 1 mWatt. During the test flight for the pattern measurement the transmitter power P_T was 5 dBW, the gain of the ground (transmitting) antenna G_T was 7.3 dBi, the multipath gain G_M was calculated to be 2.5 dB (see Fig 19B.A-1), the input power P_R of the receiver was measured by -105 dBW, line losses L were estimated by 2 dB, the distance d was 55 km and the frequency f was 335.5 MHz. As given by the mentioned gain-loss equation, the actual gain G_R of the glide slope antenna becomes

$$\begin{aligned} G_R &= -P_{T(dBW)} - G_{T(dBi)} - G_{M(dB)} + P_{R(dBW)} + L_{(dB)} + 20\log d_{(km)} + 20\log f_{(MHz)} + 32.54 \text{ dB} \\ &= -5 \quad -7.3 \quad -2.5 \quad -105 \quad +2 \quad +34.8 \quad +50.5 \quad +32.54 \text{ dB} \\ &= 0.04 \text{ dB} \end{aligned}$$

The minimum required gain G_{min} of the glide slope antenna is derived from the relation

$$\frac{A}{G} = \frac{\lambda^2}{4\pi}$$

which applies to all antennas [19B-1]. A is the effective area, G the gain of the antenna and λ the wavelength. For an isotropic antenna with no preferred direction of radiation, G is 1 and A_i becomes

$$A_i = \frac{\lambda^2}{4\pi}$$

The received power P_R in the case of an isotropic antenna is then

$$P_R = S_R A_i = S_R \frac{\lambda^2}{4\pi}$$

where S_R is the power per unit area, and in logarithmic units of measure

$$P_R = S_R + 10\log\frac{\lambda^2}{4\pi}$$

with S_R in dBW/m² and λ in m.

Now the minimal required gain G_{min} of the antenna is given by

$$G_{min} = P_{Rmin} - (S_R + 10\log\frac{\lambda^2}{4\pi})$$

As can be seen in Table 19B-I the power density S_R for a glide slope antenna is -95 dBW/m² and the minimum receiver input power is -87 dBm, which is -117 dBW. A frequency of 335.5 MHz presumed now G_{min} becomes

$G_{min} = -117 - (-95 - 11.96)$ dB

$= -10.04$ dB

The gain margin G_m already mentioned in section 19B.1.2 is the difference between the actual gain G_R and the minimum required gain G_{min}

$G_m = G_R - G_{min}$

which is

$G_m = 0.04$ dB $+ 10.04$ dB

$= 10.08$ dB

In Fig 19B.A-2, the maximum power level MPL is observed between 360 and 10 degrees at 54 dB. Then the LRP circle becomes

$LRP = MPL - G_m$

$= 54 - 10.08$ dB

$= 43.92$ dB

It is noticed, that the lowest required power level is not achieved in the angular areas from 80 to 135 and 220 to 285 degrees. But these are areas, where the glide slope system is out of use anyway.

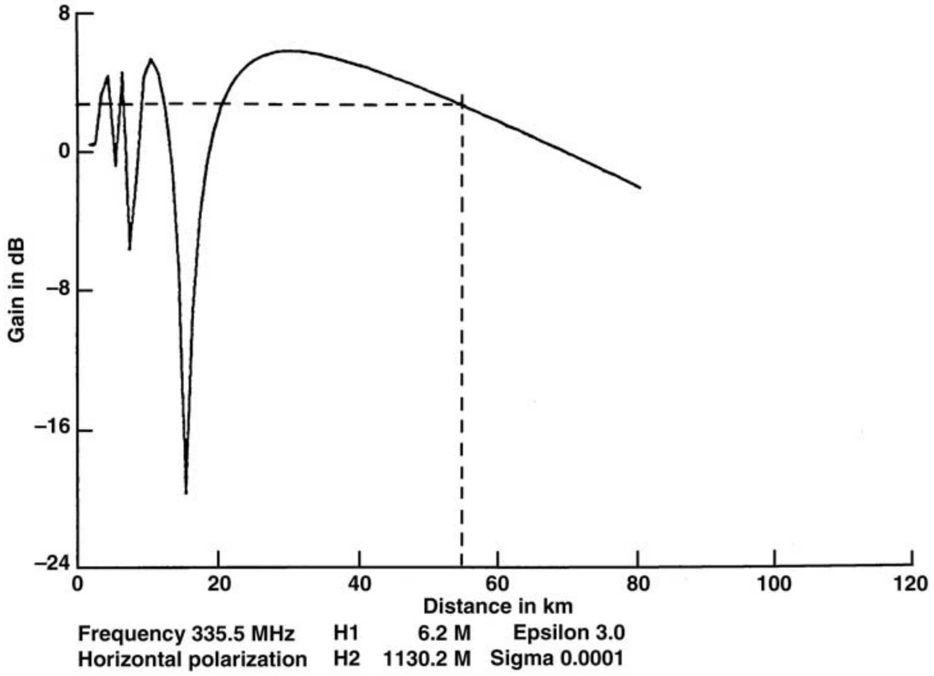

Figure 19B.A-1. Multipath Gain of the Reflecting Ground Calculated after Reference 19B-1.

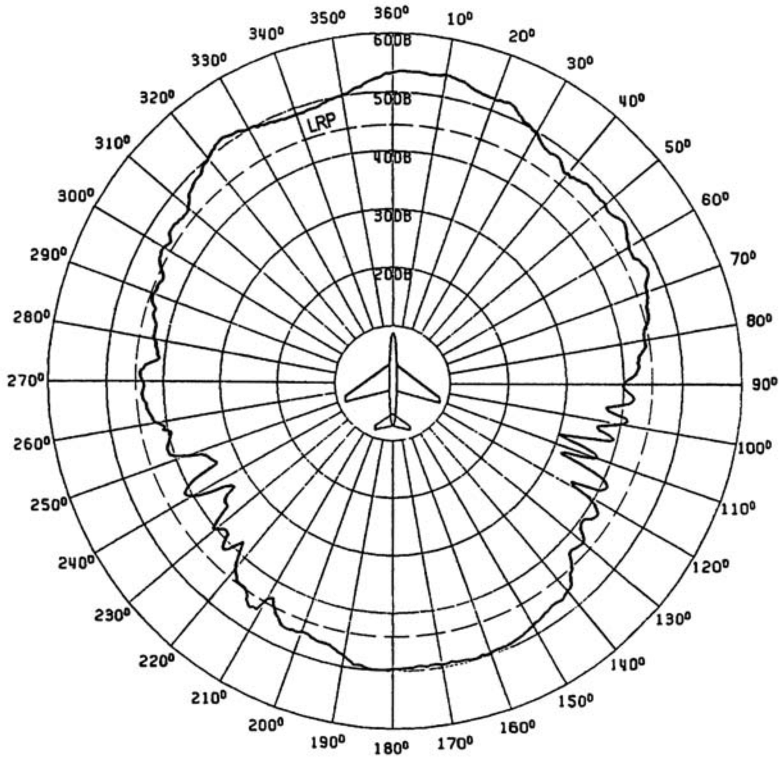

Figure 19B.A-2. Radiation Pattern of a Glide Slope Antenna, Frequency 335.5 MHz, Polarization Horizontal, Test Flight Left Circle, LRP 44 dB.

APPENDIX 19B.B – EXAMPLES OF MEASUREMENT RESULTS

The measurement results given in this section have been recorded by an automatic measurement system with on-line data processing capabilities, operated by the German Aerospace Research Establishment (DLR) in Braunschweig. [19B-12, 19B-13] The radiation pattern of a VOR/Localizer navigation antenna measured in flight is shown in Figure 19B.B-1. This antenna is built into the nose of a flight inspection aircraft Cessna Citation. The pattern shows small interferences in the tail section due to shadowing effects of the fuselage. The pattern has been recorded during a low banked circle flight.

Another example taken from the same aircraft during a fly-over trajectory is illustrated in Figure 19B.B-2. The pattern of a marker antenna mounted below the fuselage is nearly undisturbed in the angular area of operation.

If frequencies increase, the departure of the radiation pattern from circularity usually becomes much worse as the next example illustrates (Figure 19B.B-3).

The radiation pattern of a telemetry antenna mounted on top of the vertical stabilizer of a Dornier DO 228 aircraft is shown in Figure 19B.B-3. During the right-circle flight the left wing elevates and disturbs propagation in the angular area of 280 to 350 degrees. In addition the vertical stabilizer is deflected for guidance of the aircraft during the 15-degree coordinated turn. This deflection deteriorates radiation in the areas around 155 and 210 degrees.

The Dornier DO 228 test aircraft of the DLR carries a directional waveguide slot antenna below its fuselage. This antenna serves for picture data transmission in the 15 GHz frequency band. The 5-degree beamwidth in the horizontal plane asks for directional control in this plane, while the vertical beamwidth of 35 degrees requires no further control. The horizontal radiation pattern of this antenna is illustrated in Figure 19B.B-4. During the pattern measurement the main beam was fixed to a horizontal aspect angle of 90 degrees. It is observed that a high number of smaller lobes are generated by additional rays reflected and diffracted from the structure of the aircraft.

Figures 19B.B-5 and 19B.B-6 illustrate results of RCS measurements taken from the same type of aircraft by in-flight measurements and by scaled model measurements. The scaled model measurement results are averaged over an area of 5 degrees. The difference of 24dB to 6dB in the nose area of the model results from a radar antenna, first aligned in the roll axis and then turned aside. Though the scaled model results are available in limited sectional angular areas only a fairly good agreement with the dynamic results can be observed.

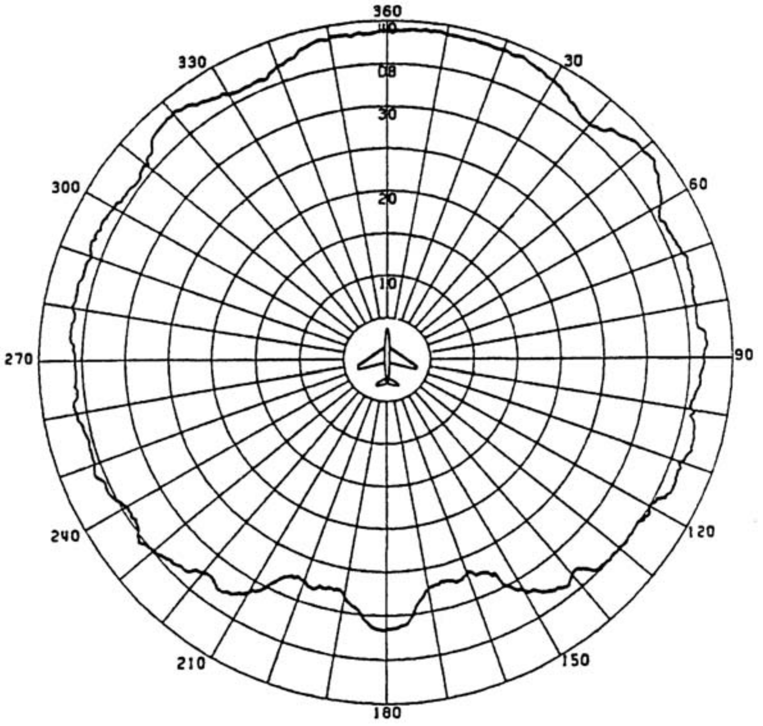

Figure 19B.B-1. Radiation Pattern of VOR/LOC Antenna, Trajectory Left-hand Circle, Bank Angle 5 Degrees, Frequency 111.1 MHz.

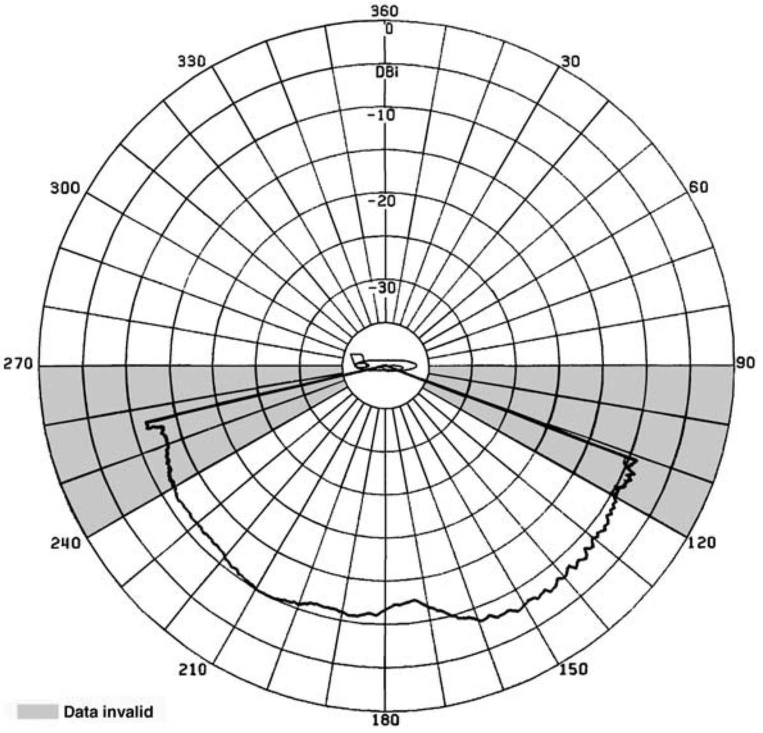

Figure 19B.B-2. Radiation Pattern of Marker Antenna, Trajectory Fly Over, Frequency 75 MHz.

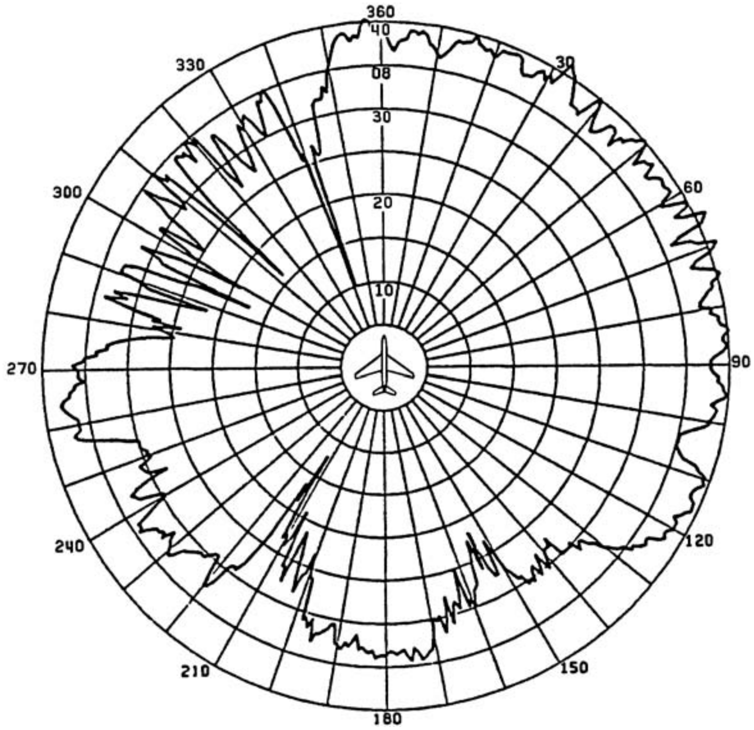

Figure 19B.B-3. Radiation Pattern of Telemetry Antenna, Trajectory Right-hand Circle, Bank Angle 15 Degrees, Frequency 2401 MHz.

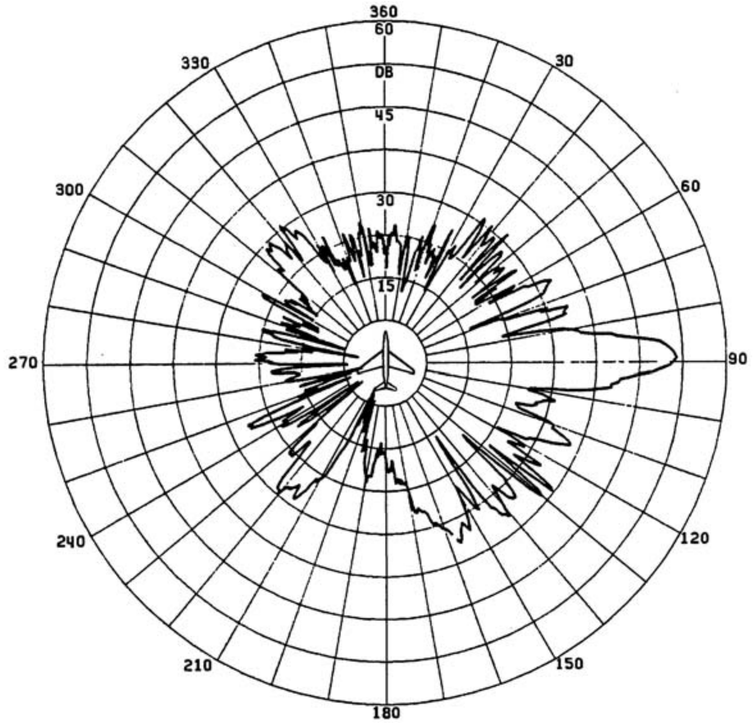

Figure 19B.B-4. Horizontal Radiation Pattern of a Waveguide Slot Antenna, Bank Angle 0 Degrees.

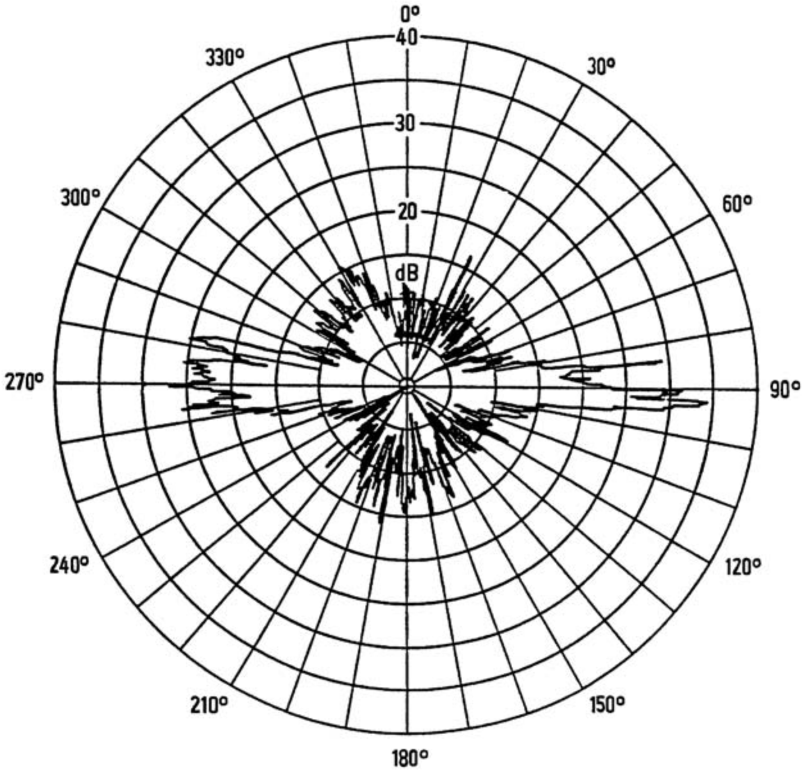

Figure 19B.B-5. In-Flight Measured RCS of Small Twin Jet Aircraft, Trajectory Right-hand Circle, Bank Angle 10 Degrees, Frequency 5 GHz, 0dB=1m².

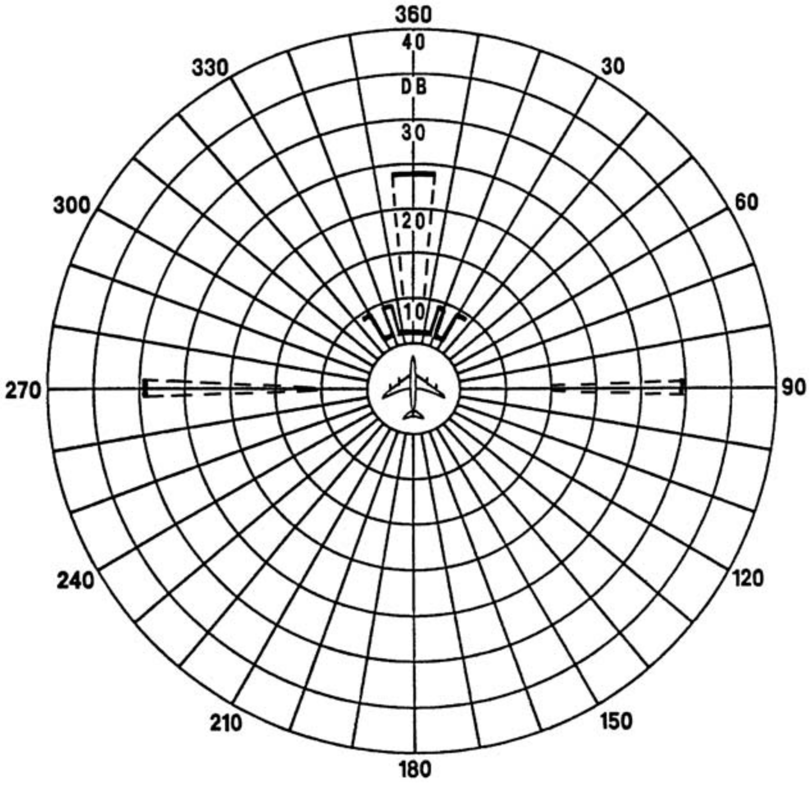

Figure 19B.B-6. RCS of Scaled Model of Test Object from Figure 19B.B-5, Bank Angle 0 Degrees, RCS Averaged over Angular Area of 5 Degrees, 0dB=1m².