National Defence Défense nationale

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL NOTE 95-1

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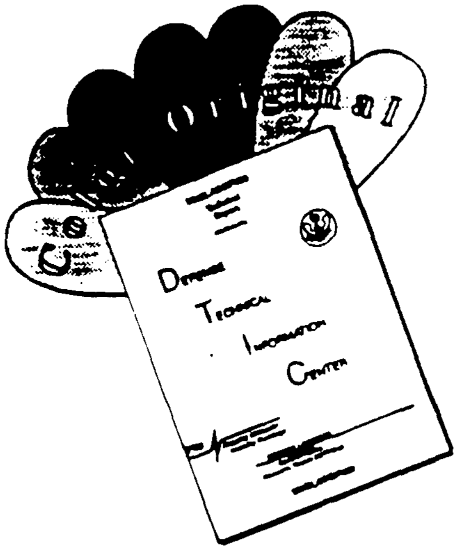

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Capt E.R. Boudriau
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ABSTRACT

The flexibility of Multiple-Beam Antennas (MBAs) for Satellite Communications (SATCOM) systems has long been recognized. Their potential to handle the ever-growing demand for increased communications requirements and their hability to communicate with a large number of earth stations have made MBAs most desirable in satellite antenna systems.

This report outlines the benefits and considerations that revolve around the use of MBAs for Military Satellite Communications (MILSATCOM) applications. It also presents some of the most commonly used MBA configurations.

The design and selection of a satellite MBA system are limited by the fundamental limitations particular to each type of MBA system. Engineers are forced to make compromises between overall antenna performance and some of the design and physical constraints presented in this report.

RÉSUMÉ

La flexibilité des antennes à faisceaux multiples (AFMs) dans les systèmes de communications par satellites est reconnue depuis longtemps. Leur potentiel de pouvoir répondre à la demande sans cesse croissante des besoins de communications et leur capacité de pouvoir communiquer avec un grand nombre de stations terrestres ont fait des AFMs un choix populaire comme système d'antennes satellites.

Ce rapport démontre les avantages et les considérations des AFMs dans les applications de communications militaires par satellites. Il présente également quelques unes des configurations de AFM les plus utilisées.

La conception et la sélection d'un système d'AFMs pour satellite sont dirigées par les limites fondamentales particulières à chaque type de AFM. Les ingénieurs doivent faire des compromis entre la performance globale de l'antenne et certaines des limites physiques et de conceptions présentées dans ce rapport.

EXECUTIVE SUMMARY

Satellite antenna designs and selections have become increasingly complex. The growing demand for increased communications satellite capacity and the ever changing requirements have led to the crowding of geosynchronous orbital slots. The solution to this growing demand is not only limited by the physical constraints imposed by the satellite on size, shape and weight of its subsystems, but also by a number of other factors such as the limited power resources and the location available in the satellite.

A Multiple-Beam Antenna (MBA) is defined as an antenna capable of creating a family of major lobes from a single nonmoving aperture. A typical satellite MBA system consists of a focusing optics subsystem illuminated by an array of feed elements. Each feed element illuminates the optical aperture and generates a constituent beam. The relative low cost and simple inclusion of more feed elements can result in an antenna system capable of producing more than one beam from the same aperture. By employing an MBA system, a single satellite antenna can communicate with a large number of earth stations, improving the communication capacity and utilization effectiveness of satellites dramatically.

This report presents some of the benefits and considerations that revolve around the use of MBAs for a Military Satellite Communications (MILSATCOM) system.

ACKNOWLEDGEMENTS

This report could not have been completed without the substantial input received on antennas and Multiple-Beam Antennas from Dr. G.A. Morin from the MILSATCOM group of the Space Systems and Technology section at Defence Research Establishment Ottawa.

CONTENTS

INTRODUCTION

The growing demand for increased communications satellite capacity and the crowding of geosynchronous orbital slots have led to more stringent demands on satellite antenna design and selection. Their design for satellite applications differs from other applications in many ways and some considerations affecting the selection of a particular satellite antenna will be addressed in this report. Although an antenna pattern varies from omnidirectional to highly directional, this report will concentrate only on highly directional antennas, and more specifically on Multiple-Beam Antennas (MBAs).

Their potential flexibility allows them to provide variable pattern shaping to accommodate changing surveillance or communications requirements and to suppress interfering signals. By employing an MBA system, a single antenna can communicate with a large number of earth stations, improving the communication capacity and utilization effectiveness of satellites dramatically. Moreover, the aperture size of earth station antennas can be reduced greatly, lowering the overall cost.

The purpose of this report is to present some of the benefits and considerations that revolve around the use of MBAs for a Military Satellite Communications (MILSATCOM) system. This report outlines also some of the most commonly used MBA technology in current and modern SATCOM systems.

The first part of this report briefly describes satellite antenna systems. The second part introduces MBA systems while describing some of the major design constraints and considerations that should be carefully examined when selecting the right satellite antenna system. A summary, found in the last part, concludes this report. Mathematical examples of some of the fundamental limitations of MBA systems are enclosed in Appendix A. Pictures of MBA components and of some experimental setups in the compact range at SPAR Aerospace are found in Appendix B.

1 -- DESCRIPTION

1.1 Satellite Antenna Systems

A communication satellite functions as a radio relay in space. Its antenna system must provide the communication link between earth stations and between other satellites as demonstrated in Fig. 1.

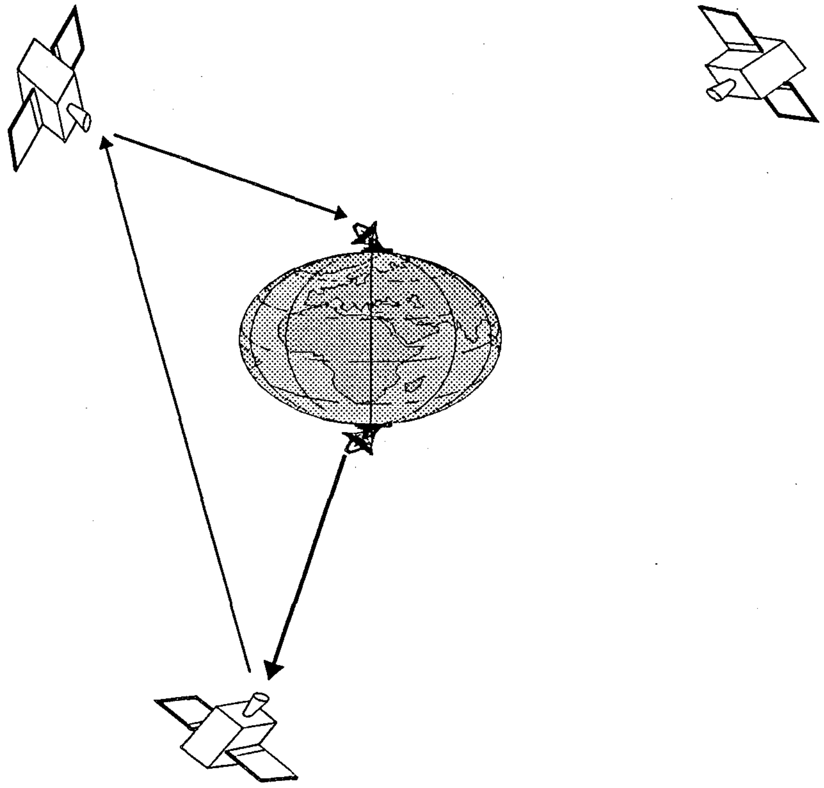


Fig. 1 Communications between two earth stations via satellite.

The design complexity of satellite antenna systems is continually increasing. The solution to the growing demand for increased communications capacity is not only limited by the constraints imposed by the satellite on size, shape and weight, but also by a number of factors such as the limited power resources available on a satellite and the location available in the satellite. However, it is still possible to increased the capacity of a particular satellite system through various techniques.

1.2 Satellite Communication Link

A communication downlink can be expressed [1] as follows:

$$A_{cov}\Delta f \cong P_t \frac{A_r}{T_s} \frac{1}{L_i} (\frac{C}{N})^{-1} \tag{1}$$

where

A_{co} = coverage area
Δf = bandwidth
P_t = satellite transmit power
A_r = earth station antenna effective area
T_s = equivalent system temperature
L_i = incidental loss
$\frac{C}{N}$ = carrier-to-noise power ratio

Increasing the communication system capacity can be achieved by increasing the effective bandwidth **Δf** through frequency reuse. With a fixed **C/N** and prechosen modulation system, the bandwidth can be increased by reducing the coverage area A_{cov} through the use of a Multiple-Beam Antenna (MBA). This divides the power among the beams while the bandwidth **Δf** remains constant for each beam. The total bandwidth available therefore increases by the number of beams.

2 - MULTIPLE-BEAM ANTENNAS

2.1 General Concepts and Characteristics of Multiple-Beam Antennas

An MBA is defined as an antenna capable of creating a family of major lobes from a single nonmoving aperture. This is accomplished through use of a multiport feed, with one-to-one correspondence between input ports and member lobes, the latter characterized by having a unique main-beam pointing direction [2]. A typical satellite MBA system consists of a focusing optics subsystem illuminated by an array of feed elements. Each feed element illuminates the optical aperture and generates a constituent beam. The relative low cost and simple inclusion of more feed elements can result in an antenna system capable of producing more than one beam from the same aperture [3]. In addition, MBA systems can have different coverage area by changing their configuration.

2.2 Multiple-Beam Antenna Configurations

An MBA can be:

a) A lens fed by an array of feedhorns (like the DSCS III satellite antenna system);

b) A reflector illuminated by an array of feedhorns (like the Ford Aerospace Intelsat V satellite antenna system);

c) A "planar" array excited by a Butler beam-forming matrix (BBFM); or

d) Some variations and/or combination of these.

Both the lens and reflectors apertures are described and illustrated in section 2.5.

2.3 Coverage Areas

MBA systems can be classified in accordance with their respective coverage area and the methodology used to cover that area. It is important to realize the fundamental differences that exist between spot-beam coverage and variable coverage antenna, often referred to as "Contoured Beam" as well as the different possible configurations between receive MBA and transmit MBA systems.

2.3.1 Spot-Beam Coverage

Satellite antennas designed to provide high gain to a point within view of the satellite are required to have directivity greater than that of a single beam illuminating the whole earth. The theoretical maximum directivity of a satellite in synchronous orbit is about 24 dB while practical considerations limit its directivity to about 20 dB [4].

For greater directivity over its Field of View (FOV) or its earth coverage, the satellite must produce a beam that scans or "steps" over the FOV. Its antenna can be steered mechanically or electronically over the FOV if a sequential raster scan is desired. However, for pseudo-random coverage of the FOV, step scans at microsecond rates are usually preferred, requiring the use of electronically controlled switches.

The FOV is covered by multiple beam footprints as shown in Fig. 2.

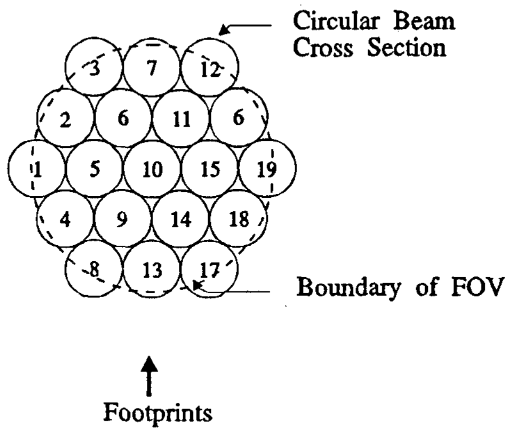


Fig. 2 Spot-Beam Coverage

Beam numbering in this figure is for identification only, and has no other meaning. A circular FOV was assumed; however, this method can be readily extended to any FOV with an arbitrary boundary. Transmit MBA systems use the reflector or lens configurations along with a switch tree. The reflector configuration is shown in Fig 3.

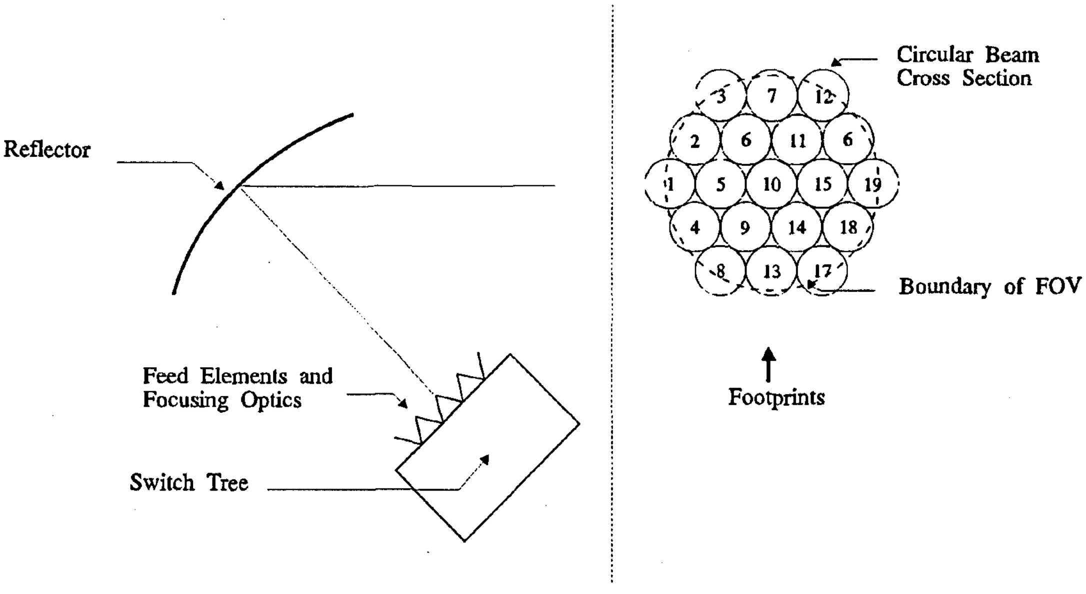


Fig. 3 Transmit MBA system using Reflector.

As in fig. 2, the beam numbering has no meaning. Usually, 1 to 4 beams are illuminated at the same time. Both the reflector and lens configuration is explained in greater detail in section 2.5.1 and 2.5.2.

Receive MBA systems also use a reflector or lens along with a variety of configurations. The least expensive configuration can be illustrated using Figure 3. This configuration has a relatively low loss and can accept 1 to 4 beams at one time as well. Being the least expensive of the configurations, it unfortunately has the highest sidelobes, at around -17 dB.

The next configuration uses a combination of switches and weights as shown in Fig. 4.

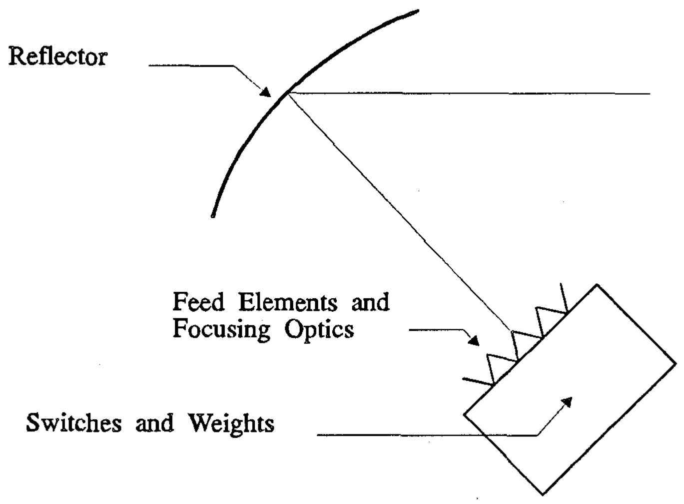


Fig. 4 Receive MBA using Switches and Weights (Shown with Reflector)

Here again, this configuration could be used with a lens. This configuration is more expensive than the first one but can also have skirt nulling capability. The diagram of the footprints, not shown in this figure, is comparable to the one represented in Fig. 3.

The last receive configuration is the most expensive one of the three discussed in this report. It uses a combination switches and weights and requires the use of amplifiers and downconverters. This configuration has a very low loss and can have low side lobes of around -30 dB. It can accept a large number of active beams and, like in the previous configuration, has skirt nulling capability. This configuration is shown in Fig. 5.

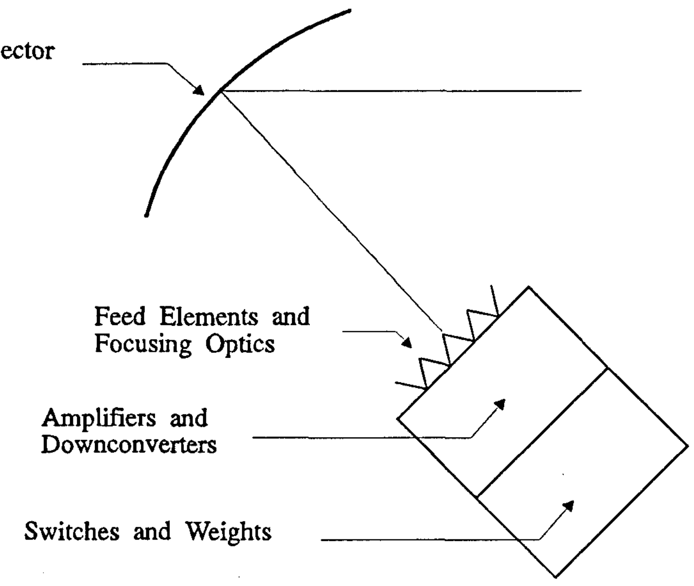


Fig. 5 Receive MBA using Amplifiers and Downconverters (Shown with Reflector)

Here again, the same configuration exists with a lens. Both lens and reflector principles are now described in greater details. As mentioned earlier, both the lens and reflector can be used for the transmit and receive MBA systems.

2.3.2 Contoured Multiple-Beam Antennas

Any shaped beam can be formed from a number of the constituent beams by the principle of superposition. The relative facility with which the MBA radiation pattern can be shaped is an important advantage. Their potential flexibility can accommodate changing surveillance or communications requirements and suppress interfering signals. The pattern shaping can be performed by using two distinct types of contoured MBA.

The first configuration is done by using an MBA system with a Beam-

Forming Network (BFN) as demonstrated in Fig. 6.

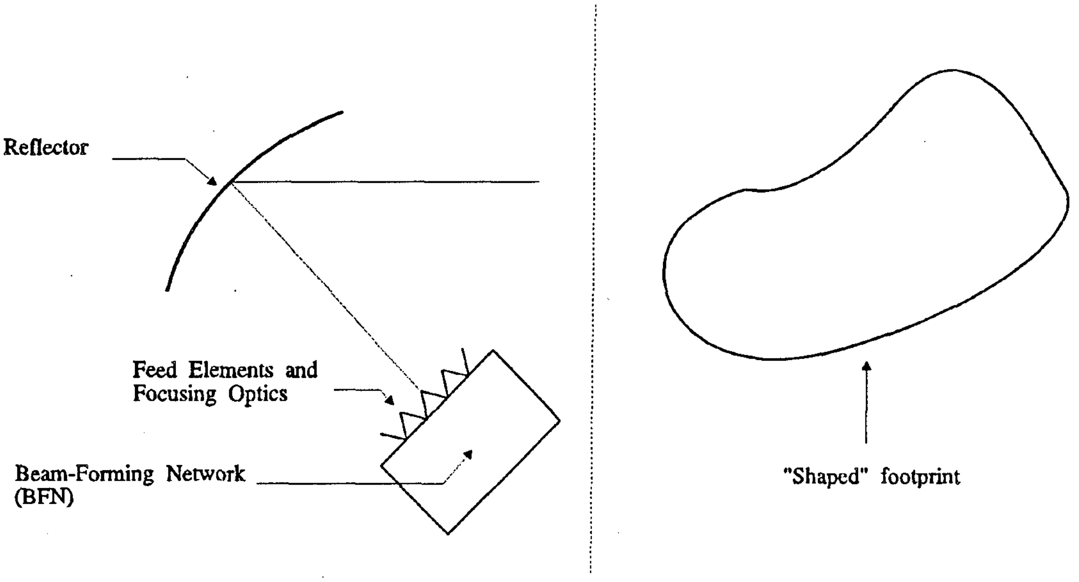


Fig. 6 Contoured MBA using a BFN.

The circuitry that divides the input power among the beam ports and/or combines the signals received from the beam ports is of prime importance and is essential to a variable coverage antenna system. The circuitry, called the BFN, is often referred to as the "heart of the MBA systems". It is responsible for providing the desired flexibility and/or control of the antenna radiation pattern shape and direction. MBA systems use both variable and fixed power dividing or combining BFNs. Their design is heavily influenced by the loss, weight and size in a satellite antenna system. BFNS can normally have three main types of switches; mechanical, ferrite, or diode variable phase shifter/variable power dividers. The selection is mostly determined by the insertion loss and switching speed requirements. A mechanically scanning beam is adopted in applications where the scanning rate is of no major concern. The beam scanning is achieved by gimbaling the antenna system. However, certain communication systems use satellite-switched time-division multiple access (TDMA) which requires a fast scanning rate that can only be achieved by using electrically controlled switches. The antenna footprint can be of any shape and can be changed by reconfigurating the beams electronically. This configuration has relatively low sidelobes and can have more than one active beam. Its directivity is inversely proportional to the footprint area. It is unfortunately expensive and requires a large reflector.

The second method of pattern shaping is achieved by using a distorted reflector and a single feed element as shown Fig. 7.

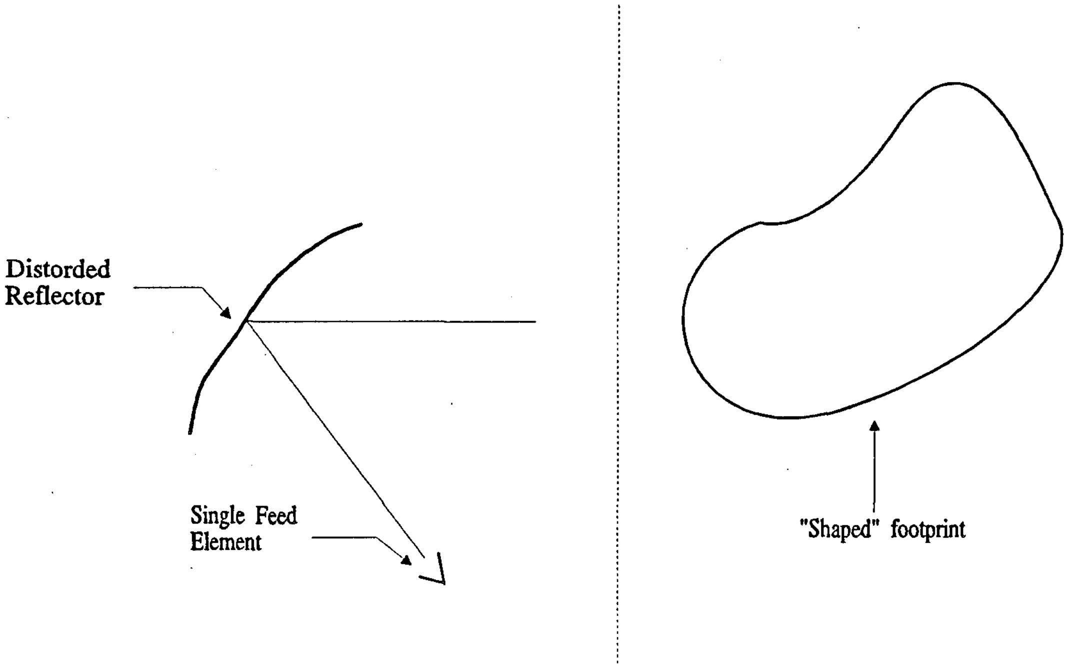


Fig. 7 Distorted Reflector Method

In this configuration, the shaped footprint can not be reconfigured. This relatively cheap solution uses a smaller reflector and a single feed. It unfortunately uses only one beam and produces high sidelobes.

2.4 Multiple-Beam Antenna Components

An MBA system consists of the following major components:

a) An optical aperture. Its function is to focus the energy from the point source to the desired direction to yield high gain. Typical types of MBA aperture are described in subsections 2.5.1 through 2.5.3;

b) A feed array. Located near the focal point, its function is to direct the energy to the aperture; and may also consist of

c) A Beam-Forming Network (BFN). This component is used for the Contoured Beam Antenna. When connected to the array, its function is to distribute the energy to the proper beam ports allowing this antenna system to shape the footprint in accordance to a particular coverage requirement as explained in section 2.3.

2.5 Basic Types of Antennas

2.5.1 Lens Antennas

The version of a lens MBA, used for the DSCS III satellite antenna, consists of an array of waveguides assembled to form a constrained lens. The waveguide lengths are adjustable, facilitating the introduction of the appropriate time delay in the signals passing through them.

A popular design technique, often referred to as the "minimum thickness lens" [3], consists of a design where the lens is made thinner and lightweight by a stepping process which allows sections of waveguides, $\mathbf{L_D}$, to be removed if the differential phase shift introduced by $\mathbf{L_D}$ equals $\mathbf{n2\pi}$ radians, where **n** is an integer. This "zoning" of waveguide lenses increases the available bandwidth but unfortunately causes a reduction of aperture efficiency, and a compromise between the weight and size constraints and the desired performance must be made. The zoning process is illustrated in appendix B, pages B - 9 and B - 10.

The lens antenna is shown in Fig. 8.

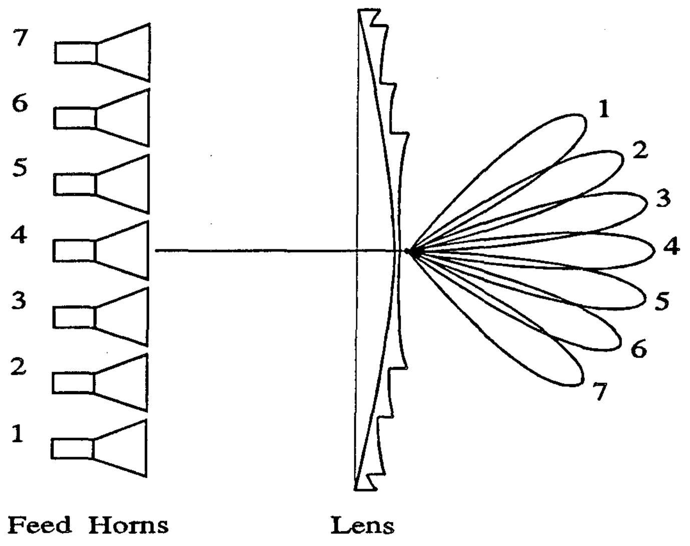


Fig. 8 Horn-lens Configuration

2.5.2 Reflector Antennas

A reflector type MBA carries the primary radiator at the reflector focus, and the beam direction can be altered by changing the position of the radiator around the focus. The reflector MBA configuration is shown in Fig. 9.

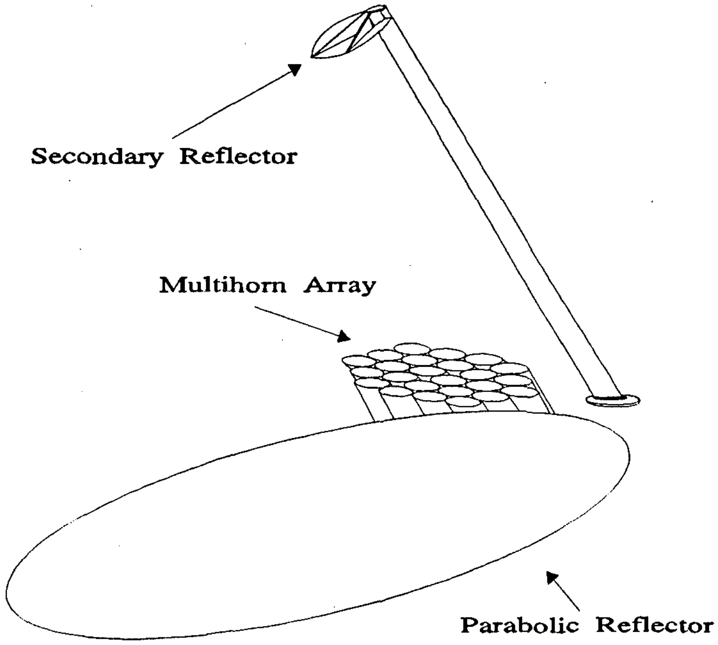


Fig. 9 Reflector MBA

The reflector type MBA's performance is similar to the one provided by lens antennas. Because the reflector type MBA employs multiple primary radiators, when a rotationally symmetric reflector is used, the radiation path is severely blocked by the subreflectors or the primary radiators. An offset reflector configuration is normally used to decrease or eliminate any degrading aperture blockage effects. An example of the calculations involved when using an offset reflector is demonstrated in Appendix A.

2.5.3 Planar Array Antennas

A Butler beam-forming matrix (BBFM), used in conjunction with a planar array antenna, possesses all the fundamental properties of an MBA. This configuration is usually preferred when the number of elements N_e ranges between a few to a few hundred. These antennas have N_e beams which span the FOV. If all elements of the array are identical and each covers the entire FOV, the space spanned by the N_e beams can be approximately defined by the half-power beamwidth of the radiation pattern of an element of the array.

3 - SPECIAL CONSIDERATIONS

3.1 General

This section outlines some of the considerations to examine before selecting a satellite MBA system. Many of the advantages and disadvantages presented in the following section can be demonstrated mathematically. However, for simplicity and to limit the scope of this preliminary report, the discussions and examples are limited to the topics that encompass important design and selection considerations common to most MBA systems. A more detailed discussions is presented in Appendix A.

3.2 Comparison of the Basic Types of Antennas

Table 1 outlines the major advantages and disadvantages of the three types of antennas discussed in section 2.

Antenna	Advantages	Disadvantages
Lens	- No feed blockage - Better scanning performance	- Heavy in low-frequency application - Aperture mismatch
Reflector	- Simple - Lightweight - Design maturity	- Offset to avoid feed blockage - Poor scanning performance
Array	- Distribution of power amplification at the elementary radiation levels - Reliable - No spillover losses - No aperture blockage	- Complex - Heavy - Higher beam-forming network losses

Table 1 Comparison of the Basic Types of Antennas

Table 1 summarizes the three major types of antennas mentioned in section 2. It is important to consider this table along with the various advantages and disadvantages associated with the different configurations presented in section 2 for both the transmit and receive MBA systems.

4 - CONCLUSION

The flexibility of Multiple-Beam Antennas for satellite communication systems has long been recognized. Their potential to handle the ever-growing demand for increased communications capacity, the changing surveillance or communications requirements, and their ability to communicate with a large number of earth stations have made MBAs most desirable in satellite antenna system. The design and selection of a satellite MBA system is limited by the fundamental limitations particular to each type of MBA but more importantly by physical constraints such as their size and weight and the location available on-board a spacecraft. Compromises between overall antenna performance and those constraints must constantly be made in order to satisfy the communications requirements.

5 - REFERENCES

[1] Lo/Lee, Antenna Handbook, Theory, Applications and Design, Van Nostran Company, N.Y., 1988.

[2] Kitsuregawa Takashi, Advanced Technology in satellite Communication Antennas - Electrical & Mechanical Design, Artech House. Boston, 1990.

[3] Rudge, Milne, Olver Knight, The Handbook of Antenna Design, Volume 1 & 2, Peter Peregrinus Ltd, London, 1986.

[4] Johnson, Antenna Engineering Handbook, Third Edition, McGraw-Hill Inc., N.Y., 1993.

APPENDIX A - ANTENNA CALCULATIONS

A.1 Performance versus Size Considerations for Spot-Beam Systems

As mentioned in section 2.5.2, an offset is necessary to decrease the degrading effects caused by the radiation path being blocked by the subreflectors or the primary radiators. Careful considerations must be evaluated when trying to minimize the gain reduction, specially when under size constraints as in the case with the limited available space on board a spacecraft. For example, we could change the position of the primary radiator to alter the beam direction by an angle Θ_e, called the *beam deflection angle*, from $\mathbf{i}_k$, as shown in Fig. 10.

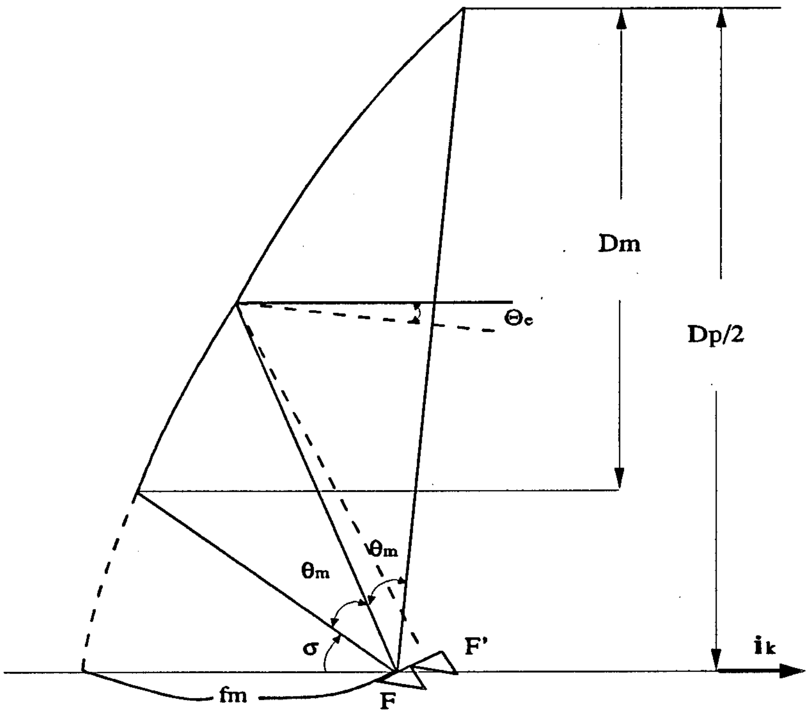


Fig. 10 Parameters of a Paraboloidal Antenna

The resulting aberration causes a gain reduction ΔG that can be approximated by the following equation [2] :

$$\Delta G \approx 5\left[1 - \cos\frac{\pi \sin\theta_e}{\left(\frac{F_m}{D_p}\right) \cdot 190\sin\theta_3\left(1 - e^{-0.12\frac{D_m}{\lambda}}\right)}\right] \tag{2}$$

where $2\Theta_3$ is the half-power bandwidth, λ is the wavelength, F_m is the focal length, D_m and D_p are the aperture diameter of the antenna and the parent parabola, respectively. The reflector configuration determines the F_m/D_p value which affects the gain reduction ΔG. The larger the value F_m/D_p is, the smaller is the gain reduction because the reflector approaches a planar configuration with smaller aberrations.

Maintaining a fixed aperture while trying to increase the value F_m/D_p leaves only two options: to decrease the value of the diameter D_p or to increase the focal length F_m. A reduction of D_p is limited by the conditions required to avoid blockage by the primary radiators. In the case of a paraboloidal antenna, D_p can not be less than $2D_m$. Increasing F_m reduces the gain loss but requires a greater distance between the primary radiators and the reflector, and so a larger antenna structure is needed. As in the case of a paraboloidal reflector antenna reflected by these calculations, design engineers must evaluate, for most MBA systems, the necessary trade-off between the overall antenna size and its gain.

A.2 Fundamental Limitations of Contoured MBA System

Design engineers often need to know the MBA pattern limitations to realize either adequate or best overall system performance. Some performance characteristics, fundamental to MBA systems, can be used as guidance in system design. Furthermore, several important concepts, such as Degrees Of Freedom (DOF), antenna Field Of View (FOV) and Antenna Resolution, have considerable effects on an antenna's performance. It is possible to understand some of the limitations imposed by those concepts on an MBA system without a complete mathematical analysis.

Fundamentally, we can realize that pattern shaping requires specification of the MBA system directive gain at a finite number of points, **P**, in the antenna **FOV**. Clearly, **P** cannot exceed the number of beams, **M**, but may be less than **M**. The parameters involved in pattern shaping must be adjusted to result in pattern shapes that are within the fundamental limitations of the antenna system. Two of those limitations, the rate of change of the antenna pattern with change in angle, and the angular separation between a pattern "null" and a pattern maximum, are strongly related to the MBA aperture size, one of the major design constraint on-board a satellite. They are referred to as "**pattern fall-off**" and "**interference-user angular separation**". Interference suppression performance, or nulling, depends principally on the aperture size **D**, the tolerable loss in gain to a desirable signal source, and the number of interfering sources. Satisfactory performance is achieved when the angular separation between the desired and interfering signal sources is less than the half-power beamwidth, **HPBW**, defined as:

$$HPBW = 1.02\frac{\lambda}{D} radians \tag{3}$$

However, when this angular separation is obtained, the directive gain in the direction of the desired signal is reduced. This loss in gain $\mathbf{L_g}$ also depends on the aperture size, the number of interfering sources and the field distribution. Looking at a scenario consisting of a single interfering source and a single desired signal subtending an angle $\mathbf{\Delta\Theta}$, measured at the nulling antenna, one can easily demonstrate this relation. The minimum loss achievable can be estimated by the following rule [3]:

$$L_g \approx 3 + (\frac{HPBW}{\Delta\,\theta} - 2)\ 3\ dB \tag{4}$$

As seen in eq. (**3**), a larger aperture would reduce this loss in gain $\mathbf{L_g}$. Once again, as in the case of most spot-coverage MBA systems, a compromise between a contoured antenna overall performance and its size must be evaluated.

APPENDIX B - PICTURES OF MBA COMPONENTS

Pictures of some MBA components can be found in pages B - 3 through B - 10. A brief description accompanying each picture or the experimental setup being shown is also included. The anechoic chamber shown in some of the pictures is located at the compact range of SPAR Aerospace, in St-Anne-de-Bellevue, Quebec.

The pictures were provided by the Multi-Media Services for National Defence at the Defence Research Establishment Ottawa. The file number associated with each picture is provided in the descriptions found on page B - 2.

PICTURES DESCRIPTION

Page B - 3: A Transmit MBA is being tested in the compact range at SPAR. The small dish on the right-hand side is for picking up a reference signal required for accurate measurements. (File No.: 92-0346)

Page B - 4: "Reflector View" of the XMBA. On the right-hand side, the feed array is mounted on a 3-axis positioner for accurate alignment of the feeds. (File No.: 92-0347)

Page B - 5: "Feed Array View" of the XMBA. The control computer is shown in the foreground. (File No.: 92-0349)

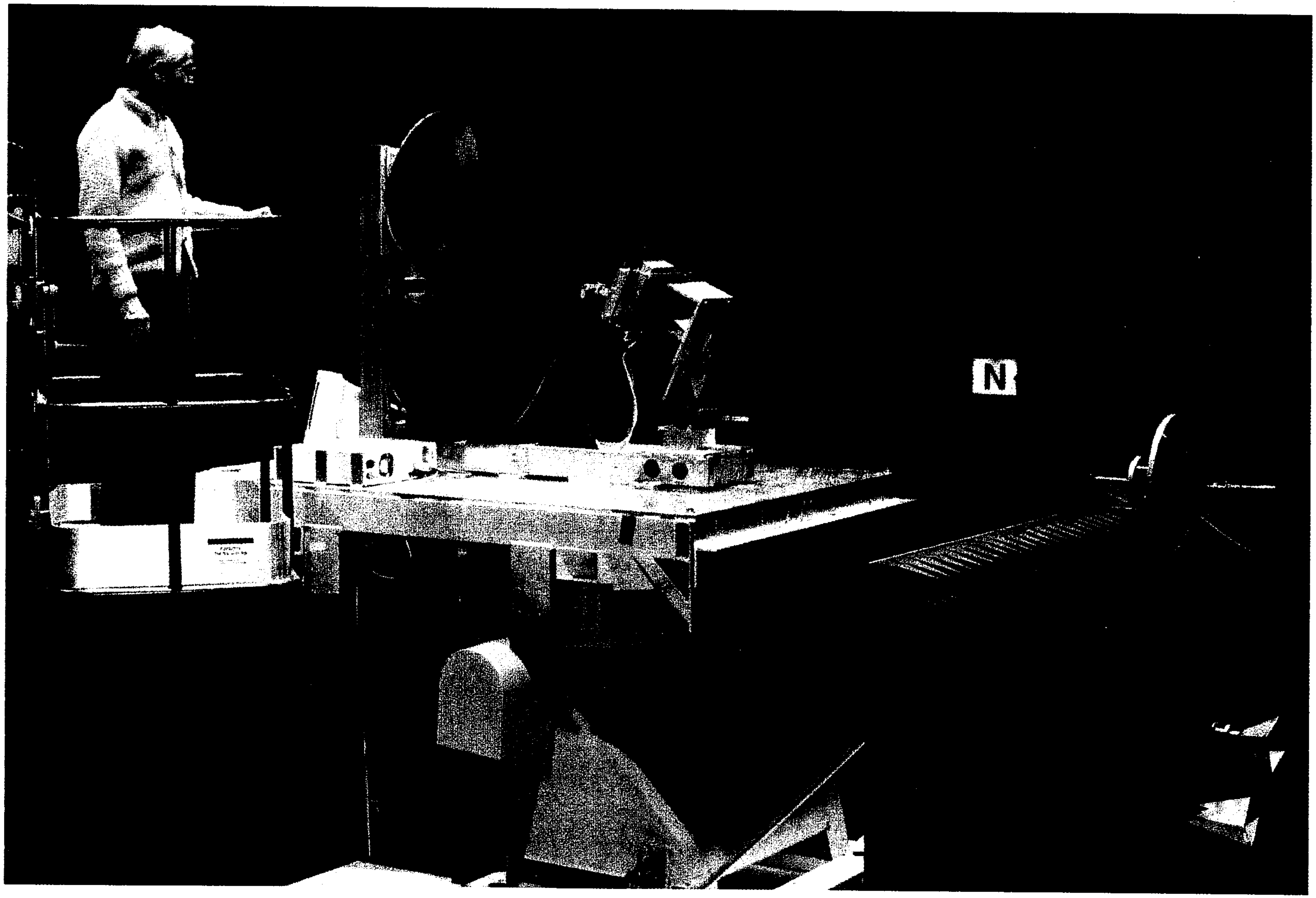
Page B - 6: Feed array mode of 7 Potter horns. The miniature screws covered with solder are part of the polarizer that makes the horns circularly polarized. (File No.: 92-0350)

Page B - 7: Feed array and 7 variable weights. The weights are controlled by computer through the large connector in the front. (File No.: 92-0352)

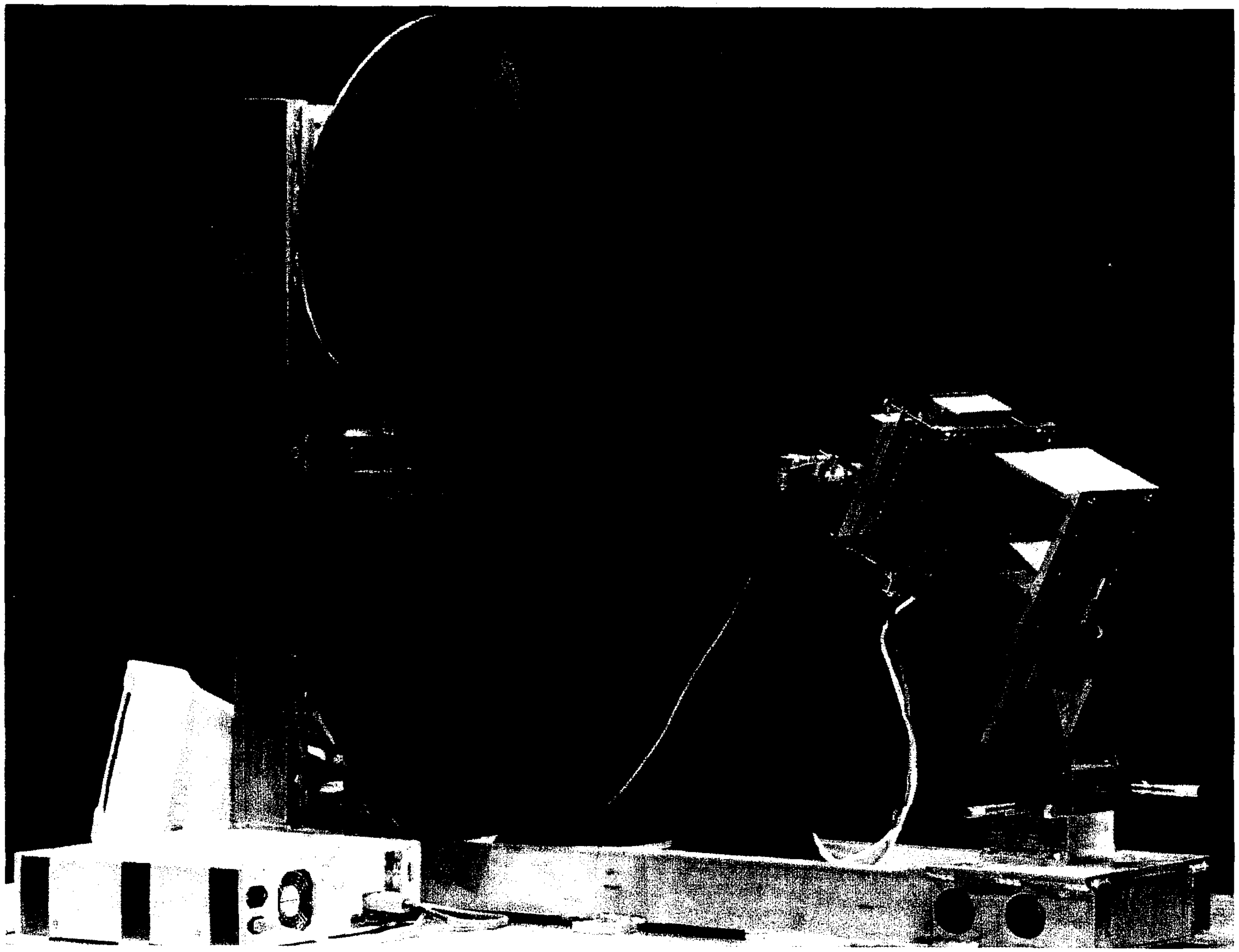
Page B - 8: Lens antenna with a single feed, on the right-hand side of the lens. The rectangular horn on the left is for gain calibration. (File No.: 94-1094)

Pages B - 9 and B - 10:

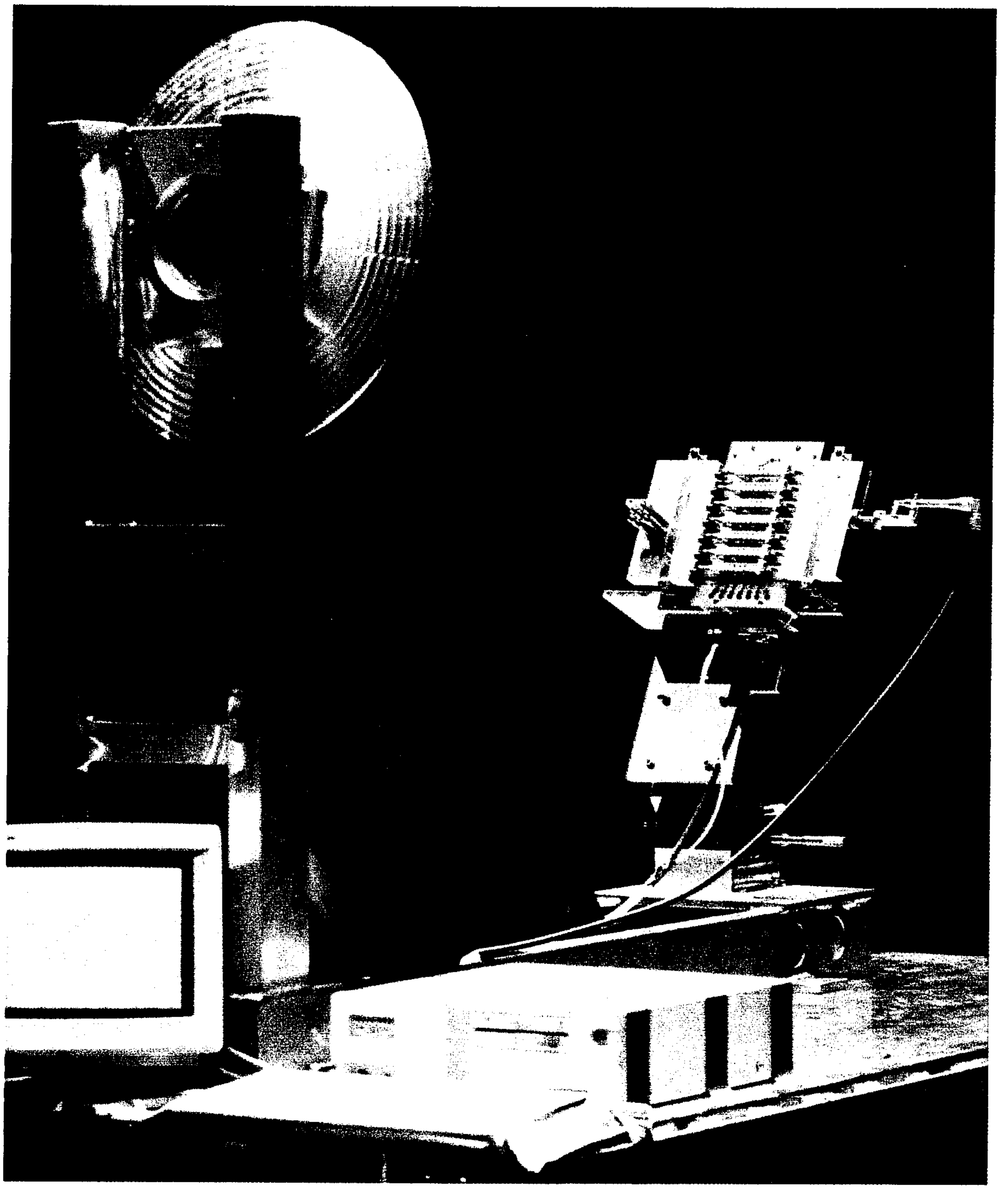
Close-up view of a shaped lens. The zoning of the lens, visible as 4 steps, is used to reduce weight. (File No.: 94-1077 and 94-1080 respectively)



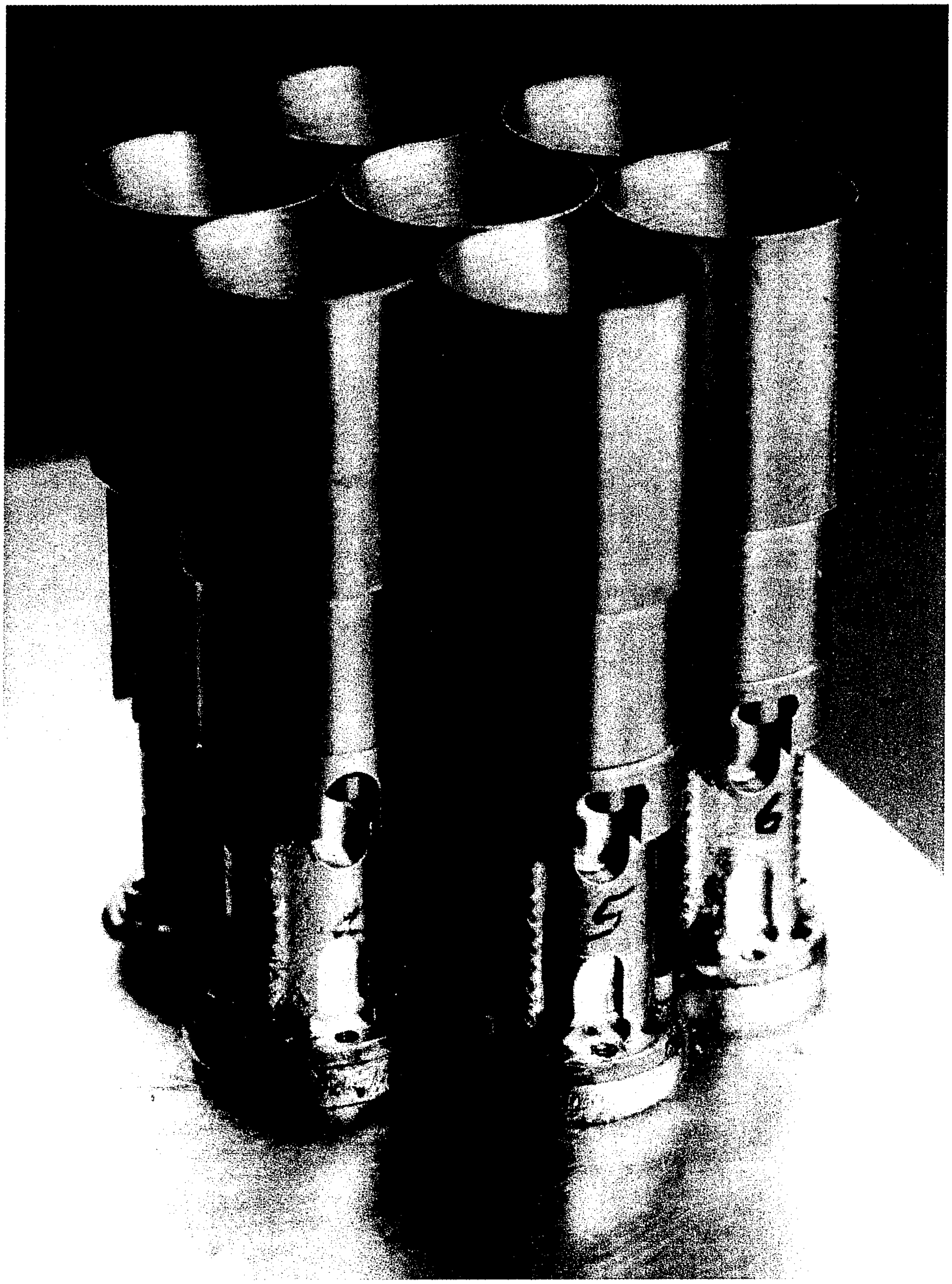
A Transmit MBA is being tested in the compact range at SPAR. The small dish on the right-hand side is for picking up a reference signal required for accurate measurements. (File No.: 92-0346)



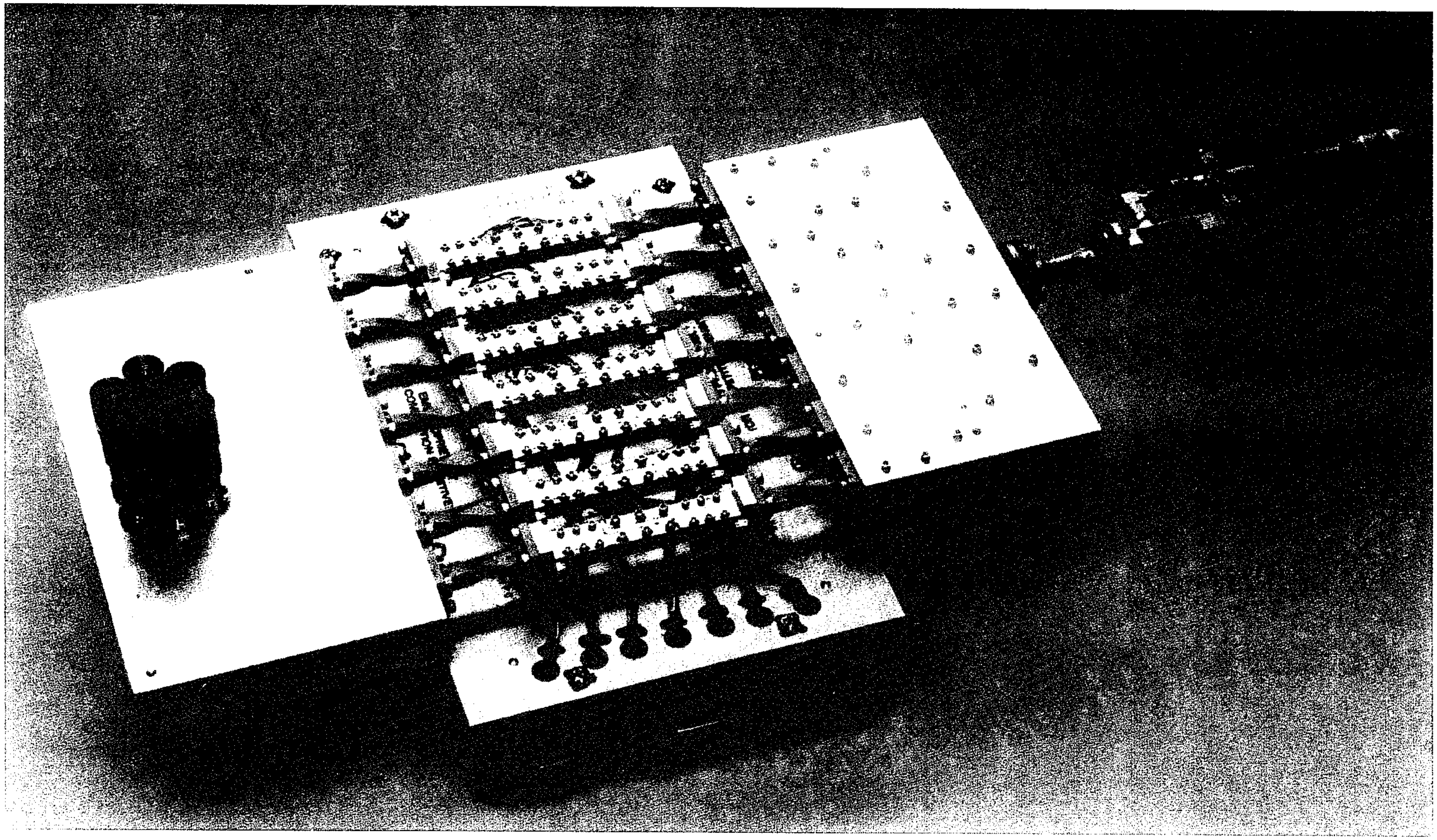
"Reflector View" of the XMBA. On the right-hand side, the feed array is mounted on a 3-axis positioner for accurate alignment of the feeds. (File No.: 92-0347)



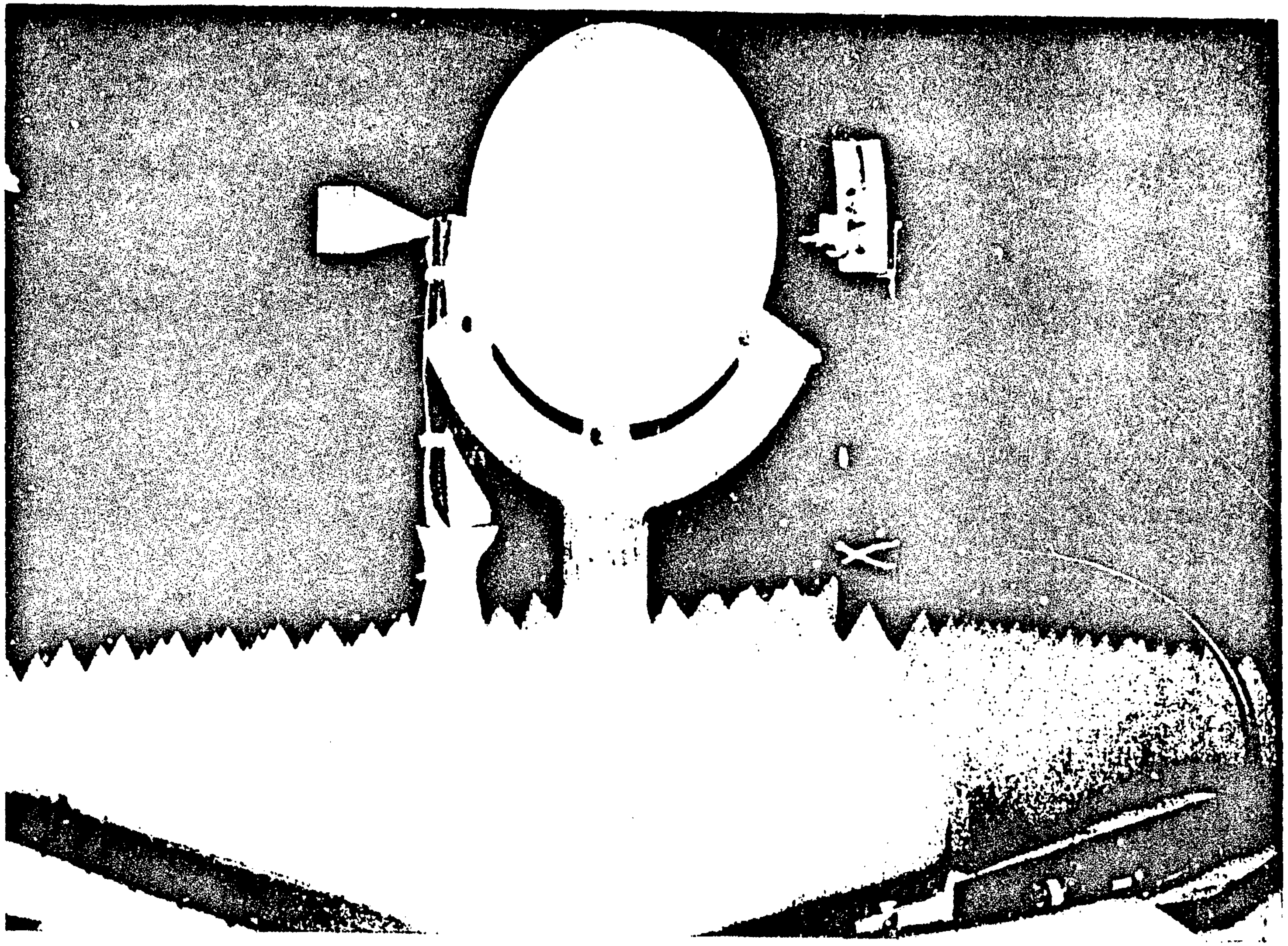
"Feed Array View" of XMBA. The control computer is shown in the foreground. (File No.: 92-0349)



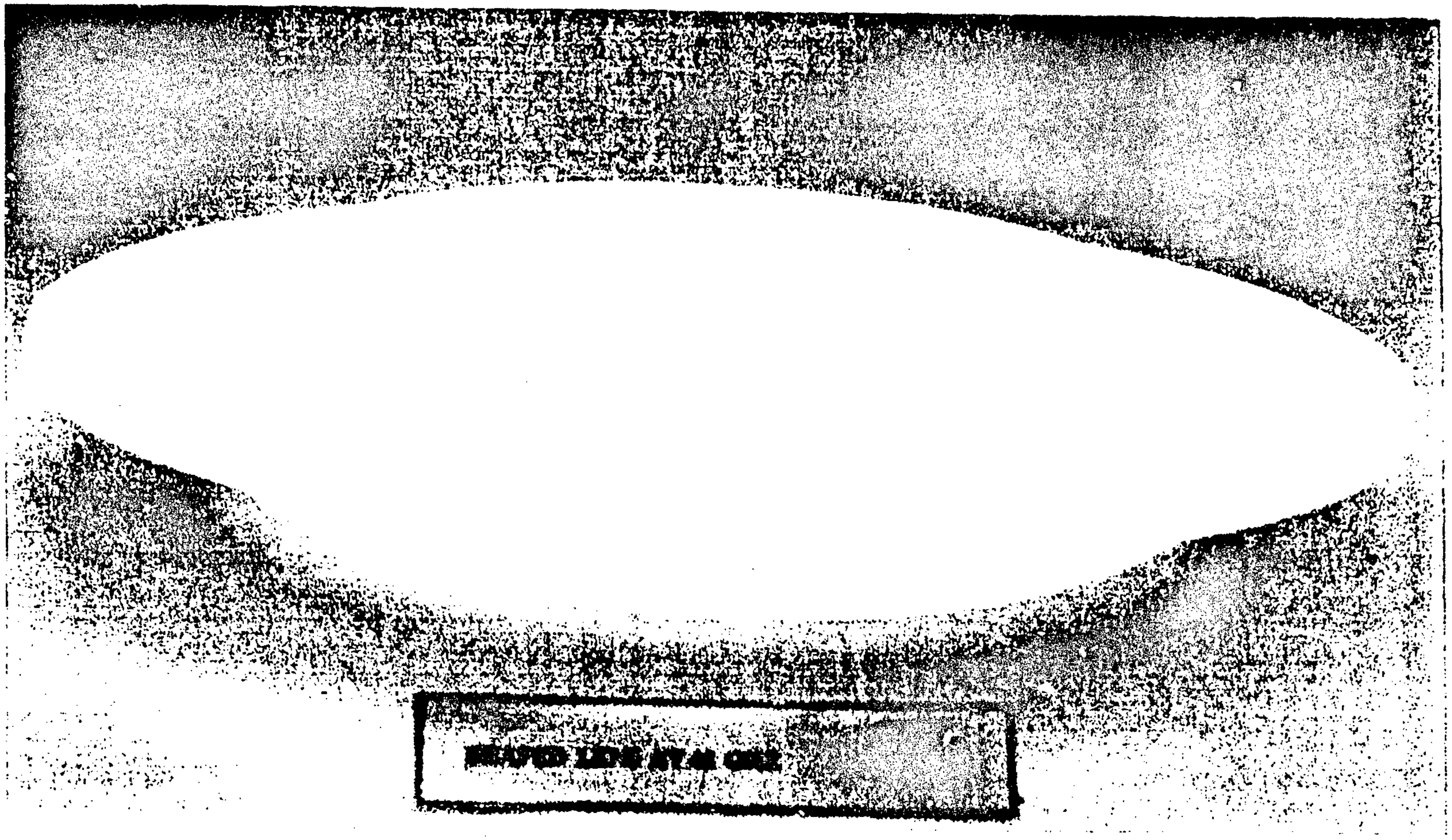
Feed array mode of 7 Potter horns. The miniature screws covered with solder are part of the polarizer that makes the horns circularly polarized.
(File No.: 92-0350)



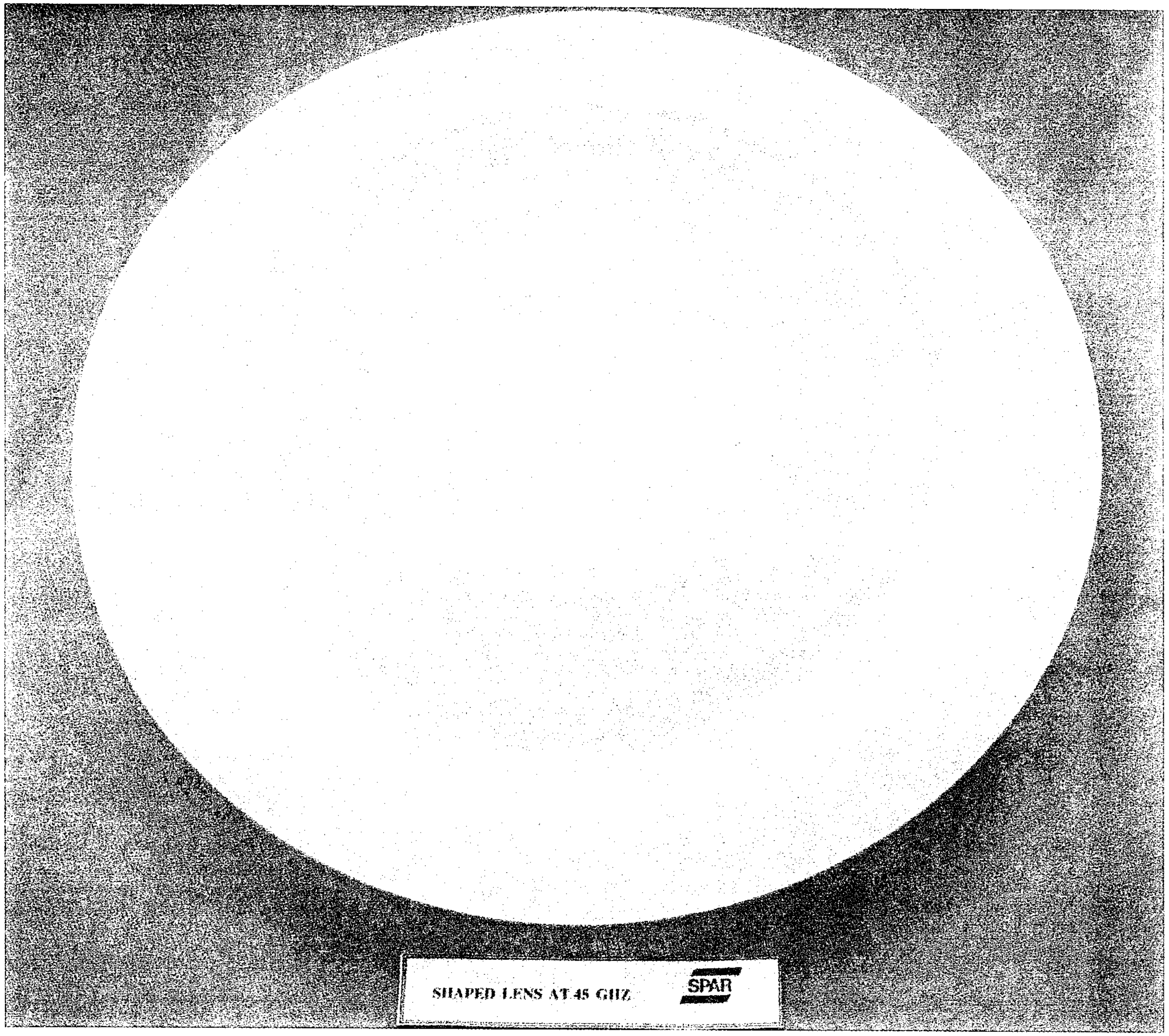
Feed array and 7 variable weights. The weights are controlled by computer through the large connector in the front. (File No.: 92-0352)



Lens antenna with a single feed, on the right-hand side of the lens. The rectangular horn on the left is for gain calibration. (File No.: 94-1094)



Close-up view of a shaped lens. The zoning of the lens, visible as 4 steps, is used to reduce weight. (File No.: 94-1077)



Close-up view of a shaped lens. The zoning of the lens, visible as 4 steps, is used to reduce weight. (File No.: 94-1080)

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The flexibility of Multiple-Beam Antennas (MBAs) for Satellite Communications (SATCOM) systems has long been recognized. Their potential to handle the ever-growing demand for increased communications requirements and their hability to communicate with a large number of earth stations have made MBAs most desirable in satellite antenna systems.

This report outlines the benefits and considerations that revolve around the use of MBAs for Military Satellite Communications (MILSATCOM) applications. It also presents some of the most commonly used MBA configurations.

The design and selection of a satellite MBA system are limited by the fundamental limitations particular to each type of MBA system. Engineers are forced to make compromises between overall antenna performance and some of the design and physical constraints presented in this report.

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