MLS—A Practical Application of Microwave Technology

RICHARD M. COX, MEMBER, IEEE, AND JAMES R. SEBRING

Abstract—**A brief system overview of the U.S. candidate of the microwave landing system (MLS) is presented. Practical implementation of two types of ground antenna designs are presented, including measured data. Phased array designs are presented as high-performance implementations. Lens array designs have proven to be acceptable solutions for limited-scan medium-performance requirements.**

Introduction and System Overview

IN 1939, the CAA demonstrated the first commercial ILS at Indianapolis, IN. Since that time, ILS use has expanded rapidly and was adopted as the international standard by ICAO in 1949. As more demands were placed upon the ILS, its limitations became well known, and efforts to develop a replacement system were initiated by the FAA in the late 1950's. Impetus toward a national solution to the landing guidance problem was provided by a letter from ATA to the FAA in October of 1967. As a result of this, special committee 117 (SC-117) of the Radio Technical Commission for Aeronautics (RTCA) was formed in December 1967 to develop "... a precision guidance system concept for approach and landing and an associated signal structure. This concept and signal structure shall satisfy, to the maximum extent possible, the various operational needs of the several classes of users."

With the technical background of SC-117, the U.S. Government formed an interagency planning group chartered to develop a coordinated national plan for microwave landing system (MLS) development. The plan formulated by this group provided for FAA leadership and development of a coordinated MLS for subsequent submission to ICAO for consideration as an international standard.

The system which has emerged from the FAA development program as the U.S. candidate system to ICAO is the scanning beam system using a time reference signal format. This technique will be prototyped and tested in various configurations during the next year under FAA sponsorship.

Basic Requirements for the New MLS

The basic requirements for the most comprehensive MLS configuration (known as the expanded configuration) provide ICAO category IIIC services when installed on a suitably equipped runway as shown in Fig. 1. The services provided are:

—Proportional azimuth angle guidance up to $\pm 60°$ relative to runway center line with vertical coverage at least to $+20°$. This service is provided with a 13.33-Hz update rate. Lower coverage of approximately 8 ft is provided for azimuth rollout guidance.

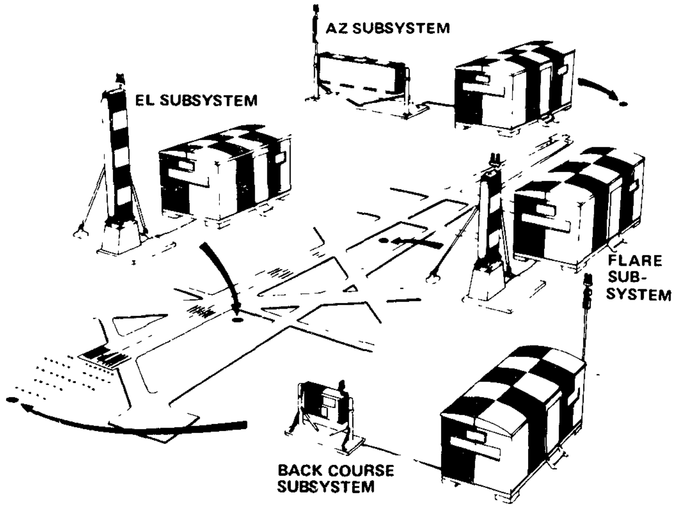

Fig. 1. Installation on a typical runway.

—Proportional back azimuth (missed approach) guidance up to $\pm 40°$ relative to runway center line at a 6.67-Hz update rate.

—Proportional elevation guidance from 0 to 20° with a 40-Hz update rate.

—Proportional flare elevation guidance from -2 to $+8°$ (consideration is being given to extending this to $+15°$) with a 40-Hz update rate.

—Range to GPIP (touchdown) and range to end of runway after strut switch actuated is provided by an independent DME subsystem.

—Basic data prior to each angle function, including function identification, ground system status, airport identification, azimuth deviation sensitivity scale factors, nominal glide slope, and minimum selectable glide slope.

—Auxiliary data in blocks of 5, 10, or 15 ms which will transmit fixed siting data and growth capacity for variable data transmitted every 75 ms at a 15-kbit rate.

—Time allocated in the format for the addition of an optional 360° azimuth signal with a 6.67-Hz update rate and a proportional back elevation function.

—Serves runways up to 14 000 ft long.

MLS Signal Format

The MLS signal format uses time division multiplexing (TDM) of all functions using a common carrier frequency at C band. The entire format is synchronized, and guard times are included within the function time slots. The beam

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The authors are with the Microwave Landing System Program, Bendix Communications Division, Baltimore, MD.

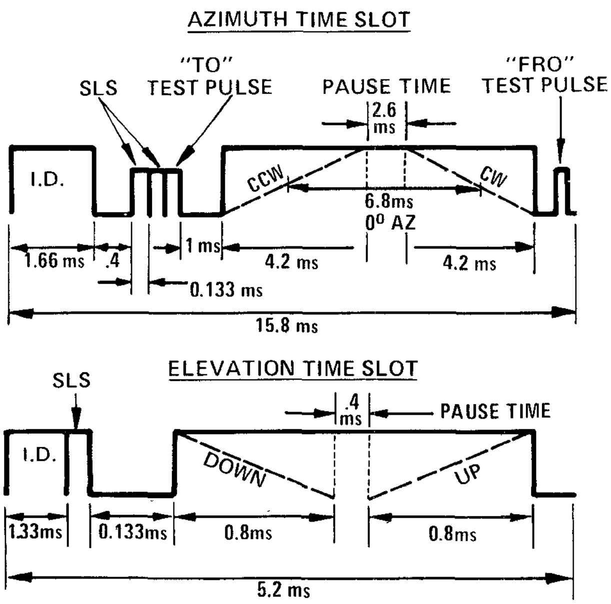

Fig. 2. Function time slots.

scan rates and angle encoding rates for the format are as follows:

Function	Beam Scan Rate (deg/s)	Angle Encoding Rate (μs/deg)
Azimuth	20 000	100
Back azimuth	20 000	100
Elevation	20 000	100
Back elevation	20 000	100
Flare	10 000	200
360°	60 000	33.33

Data are transmitted using differential phase shift keying (DPSK) of the RF carrier at a 15-kbit data rate. This technique is used to transmit elementary data on the omni ID signals at the beginning of each function time slot, and to transmit auxiliary data.

The standard scan format incorporates a variable-length auxiliary data time slot at the end of each basic 70-ms data group. Auxiliary data blocks of variable lengths are used to provide data time jitter, which serves to prevent synchronization with periodic interference effects such as propeller blockage. The lengths of the data blocks which are successively transmitted to jitter the data are 5, 5, 10, 10, 15, 15, 10, 10, 5, 5, 10, 10 ··· ms. Thus the azimuth data period, for example, is successively 70, 70, 75, 75, 80, 80, 75, 75, 70, 70, 75, 75 ··· ms and the average azimuth data period is 75 ms.

Fig. 2 shows the typical azimuth and elevation time slots. Each time slot consists of a sector omni ID transmission of elementary data, followed by transmission of one, two, or three sidelobe suppression (SLS) pulses, as necessary, followed by the high-speed "to–fro" beam scan. The omni ID signal is a data signal transmitted on a "sector omni" antenna which covers the function guidance volume. These elementary data are coded and transmitted like auxiliary data, using DPSK on the RF carrier at a 15-kbit rate. The SLS pulse(s) are transmitted on sector omni antennas with radiated power levels exceeding the scanning beam antenna sidelobe levels with sufficient margin (4-dB minimum including fade and pattern margin) to set the receiver threshold levels high enough to prevent acquisition of scanning beam antenna sidelobes outside the coverage region.

The omni ID signal is typically 1.667 ms long and provides up to 25 bits of elementary data. The SLS pulses and test pulses are 133 μs long. Guard times are not required between functions within a time slot but a guard time of 300 μs is provided between function time slots. The angle measurement is simply a problem of determining the elapsed time between the centroids of the "to" and "fro" beams. Zero degrees in azimuth is defined as 6.8 ms between beams and 0° elevation is defined as 0.4 ms between beams.

The data update rates for the standard scan format are as follows:

Function	Update Rate (per second)
Azimuth	$13\frac{1}{3}$
Back azimuth	$6\frac{2}{3}$
Elevation	40
Back elevation	$13\frac{1}{3}$
Flare	40
360° azimuth	$6\frac{2}{3}$

TABLE I
GROUND SUBSYSTEM FAA EXPANDED CONFIGURATION

PARAMETER	PRIMARY AZ ANGLE	PRIMARY EL ANGLE	FLARE GUIDANCE ANGLE	BACK AZ ANGLE	DME
Beamwidth	1.0° AZ 0-20°EL	1.0° EL 120° AZ	0.5° EL ±20°AZ	3° 0-20°EL	0–20 EL Front 120° Back 80°
Scan Coverage	±60°	0.5-20°	-0.25–8°	±40°	NA
Antenna Gain (inc. Losses)	31.4 dB	21.5 dB	29 dB	25.5 dB	Front 15.5 dB Back 15.5 dB
Transmitter Power	10W	10W	10W	10W	Front 25 kW Back 2 kW
Range	20nmi(1)	20nmi(1)	8nmi(3)	5nmi(1)	Front 20nmi(1) Back 5 nmi
MTBF	1450 hrs	3500 hrs	2800 hrs	2800 hrs	2400 hrs
Input Power	3.5 kW	2.2 kW	2.2 kW	1.0 kW	1.4 kW

(1) 25 mm/hr rain over entire area plus 5.0 nmi cell with 50 mm/hr rain
Redundance: Equipment, dual (Back Course AZ. Single)
Monitors, triple
(2) Per MIL-STD-781
(3) 8 nmi in 15 mm/hr, 2.5 nmi in 50 mm/hr rain

TYPICAL EXPANDED CONFIGURATION GROUND INSTALLATION

This configuration represents the "top of the line" in the continuum of modular systems that is provided to fill the spectrum of civil users' needs. The expanded configuration has been designed to provide full category III service at permanent airport installations with runways up to 14 000 ft in length with little site preparation. Fig. 1 depicts the installation on a typical runway. Other configurations are matched to the desired category of service, i.e., CAT I or II.

Table I summarizes the ground system specifications.

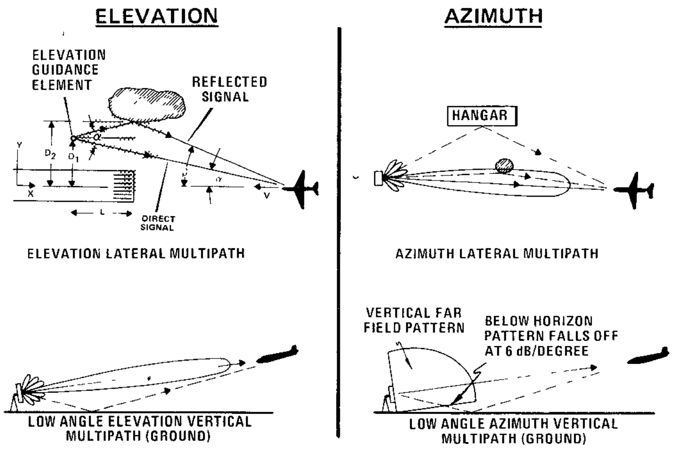

Fig. 3. Environmental effects on antenna design.

Airborne Equipment

The receiver/decoder, in conjunction with appropriate C-band antennas and a suitable flight control system, will provide the following services:

—Fail passive category III autoload with dual system configuration.

—Curved approach guidance.

—Missed approach guidance.

—360° airborne azimuth coverage.

—200-channel capability.

—20-nmi minimum range with expanded ground system.

—Reliable guidance in the presence of multipath from time reference scanning beam angle guidance encoding.

—Distance information is provided by an independent DME subsystem.

Environmental and Siting Factors Affecting Design

Some of the environmental problems impacting the design of MLS antennas are shown in Fig. 3. The major problem is multipath in both the azimuth and elevation planes. Designs to minimize the multipath problem are implemented in both the airborne and ground equipment. In the airborne receiver, certain processing techniques are employed to distinguish between direct and multipath signals. On the ground, the problem is controlled with the antenna design.

For elevation antennas, Fig. 3 indicates both lateral and vertical multipath. The lateral multipath is controlled by shaping the azimuth pattern of the elevation antenna, and minimizing radiation in out-of-coverage regions. The vertical multipath is controlled by achieving very good antenna pattern sidelobes in the elevation plane. For antennas that must scan to very low angles, such as the flare antenna, special transmitter "power programming" is used to minimize radiation into the ground.

For the azimuth case, the vertical multipath is controlled by using vertical aperture to achieve sharp underside cutoff on the elevation pattern, thus minimizing the radiation into the ground. A 4-ft vertical aperture is used to provide 8-dB/degree rolloff of the pattern at the horizon. The lateral multipath is controlled by achieving narrow antenna beams with low sidelobes in the azimuth plane.

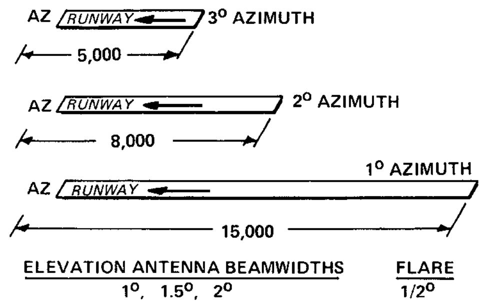

Fig. 4. MLS antenna beamwidths.

The MLS ground antenna beamwidths are runway-length dependent, as shown in Fig. 4. When landing an aircraft, one is interested in displacement error at threshold or touchdown, and, since all errors are generally beamwidth dependent, the azimuth antenna beamwidth must be a function of runway length. The beamwidth of the elevation antenna is determined primarily by the service category (categories I, II, or III) since distance from threshold is relatively independent of runway length. Categories I and II have decision heights of 150 and 50 ft, respectively, with specified decision height windows. In category III, the aircraft must pass through the category II decision height window, and must meet a prescribed touchdown location dispersion. The linear error requirements for the various categories result in elevation beamwidth requirements of 1.0, 1.5, and 2.0°. In addition, the flare antenna, used only in the category III system, must have a beamwidth of 0.5°.

Ground Antenna Implementation

C-band line array antennas with pattern shaping in the non-scan plane have been implemented for all antenna beamwidths in the 0.5–3.0° range with accuracies of 0.01–0.10 beamwidth. Two types of array antennas have been implemented. The first type is the classical line phased array configuration, consisting of a discrete aperture, a phase shifter per element, and an RF power-distribution network. The phased array, because of the degree of amplitude and phase control, is a very-high-performance antenna over wide scan angles. This antenna is used to satisfy the 0.5 and 1.0° high accuracy requirements.

The second type of antenna used is the lens array, consisting of a discrete aperture, a parallel plate lens, and a commutation network. The lens antenna is limited in the degree of amplitude and phase control achievable at the aperture plane, and, in general, is a lower performance antenna than the phased array. The beam steering in the lens array is achieved by commutating an amplitude function along the parallel plate lens input. The lens antenna is used to satisfy the 1.5–3.0° requirements, and is very attractive, from the standpoint of cost, for limited-scan requirements.

Both types of arrays are equally applicable to azimuth and elevation scanners. In fact, the radiating apertures are identical for both the phased arrays and lens array antennas.

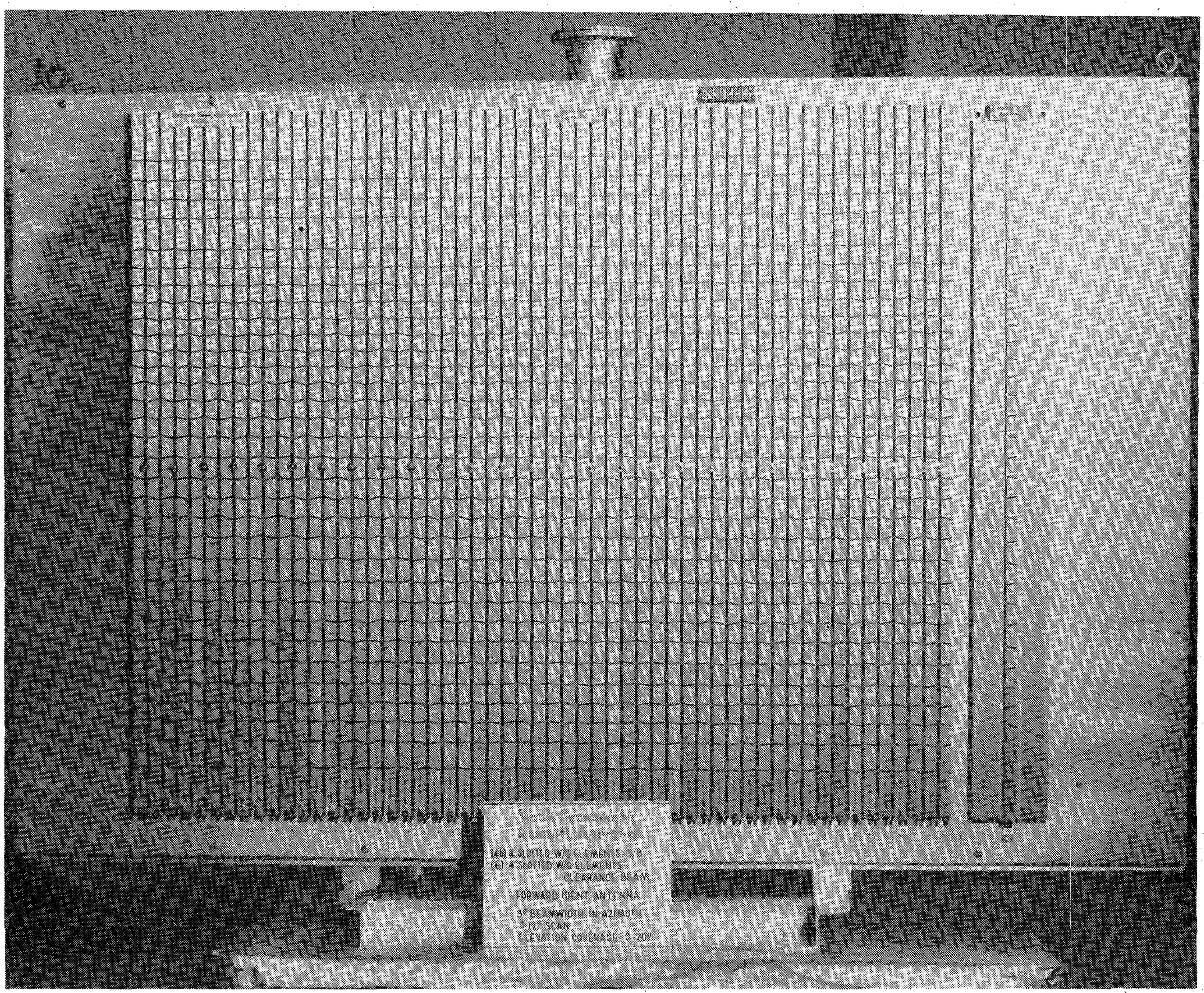

Fig. 5. Small community azimuth aperture.

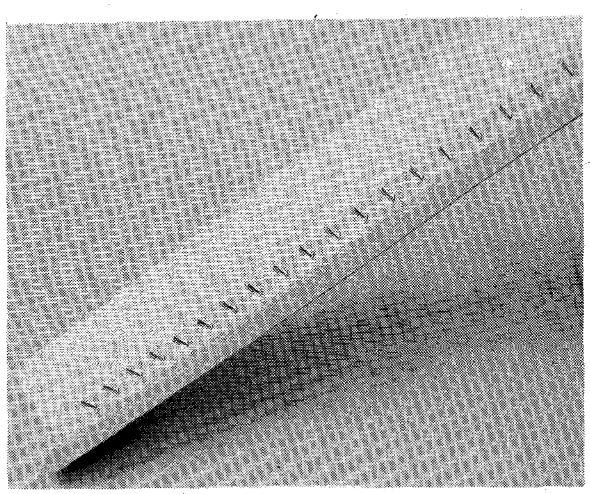

Fig. 6. Elevation aperture assembly.

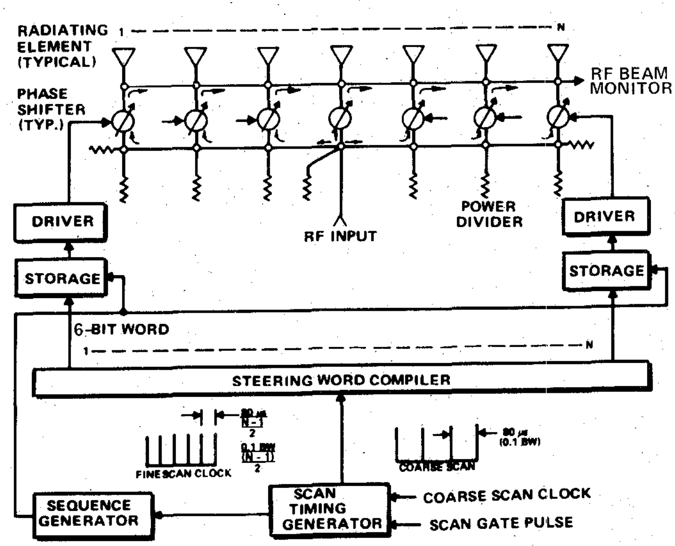

Fig. 7. MLS phased array antenna block diagram.

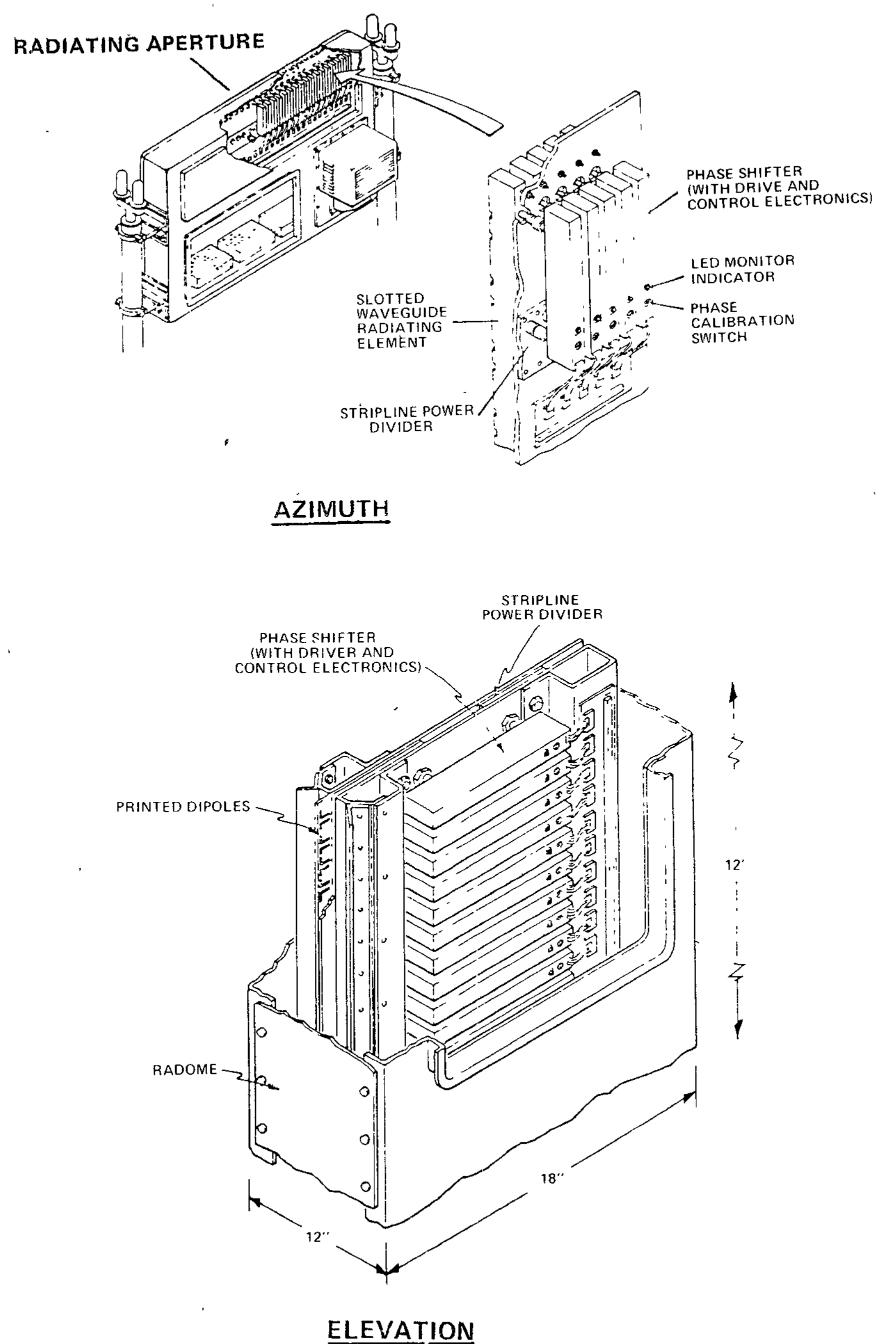

Fig. 8. Construction of azimuth and elevation phased arrays.

The azimuth and elevation aperture assemblies are shown in Figs. 5 and 6. The polarization is vertical in both cases. The azimuth aperture assembly consists of an array of coaxial-fed edge-slotted waveguide elements, with element spacings from 0.5 to 0.6λ depending on the scan requirements. Each waveguide element has 4 ft of aperture (31 slots) in the vertical plane, to provide the shaped pattern for multipath control and the upper angle coverage. The use of array aperture technology in both planes of this aperture results in maximum utility of the antenna size.

The elevation aperture consists of a colinear array of coaxial dipoles in a shaped ground plane. Element spacing is typically 0.75λ, consistent with the limited elevation scan (0–20°). The dipole ground plane is shaped in the azimuth plane to increase antenna gain on runway center line and minimize pointing errors due to lateral multipath. The pattern in the elevation plane is a scanning beam with good sidelobe control. Both coaxial and printed-circuit dipoles have been implemented, and there is little difference in cost or performance.

Phased Arrays—1° Beamwidth High Precision

A block diagram of the phased array antenna is given in Fig. 7. The array can be divided into four major sections: 1) the radiating elements; 2) the phase shifters; 3) the RF power divider; and 4) the beam steering electronics. The

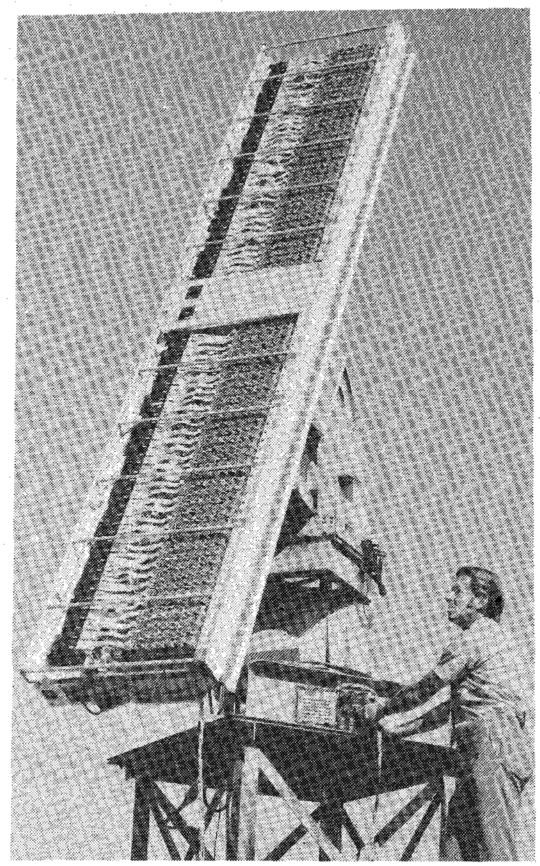

Fig. 9. Elevation array.

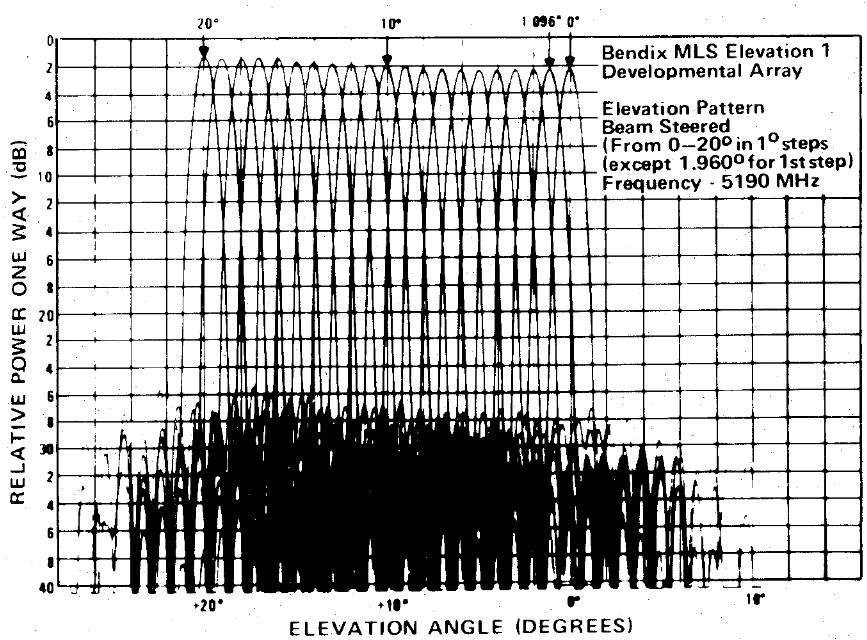

Fig. 10. Static-type scan pattern (EL-1).

apertures are, as described previously, either slotted waveguide or coaxial dipole elements. The phase shifters are 4-bit digital, with a phase accuracy of 12° peak, 5° rms. A center-fed series-type power divider generates a 27-dB Taylor amplitude illumination function with minimum cost and complexity. Frequency compensation and array calibration are economically performed with logic input adjustments at the element phase shifters. The beam steering unit scans the beam at a rate of 20 000 °/s. A coarse/fine-scan technique provides coarse-scan increments of 0.1 BW, and fine-scan increments of $[(0.1\ \mathrm{BW})/((N-1)/2)]$, where N is the number of array elements.

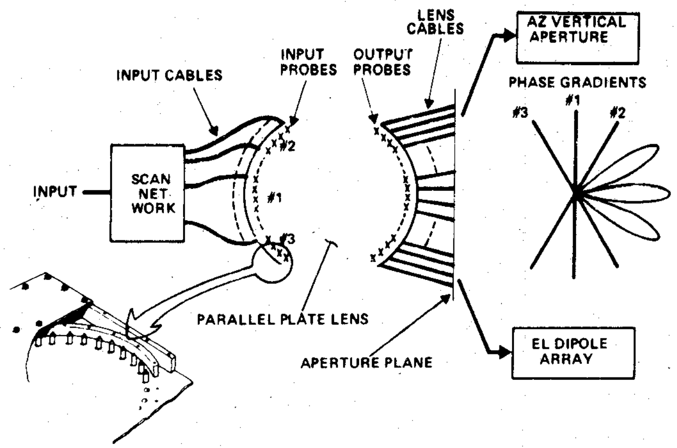

Fig. 11. Lens array concept.

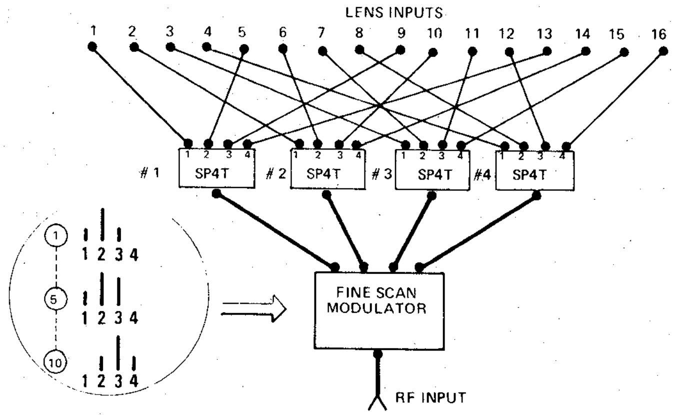

Fig. 12. Scan network for 1.5° beamwidth antenna.

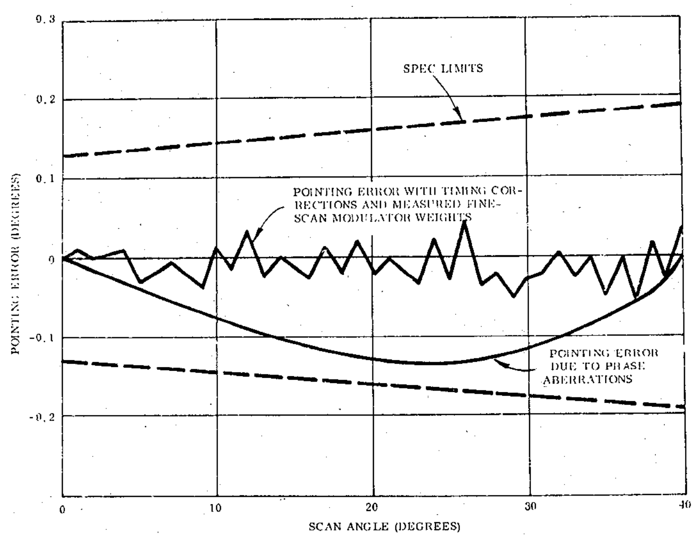

Fig. 13. Computer beam-point error curve.

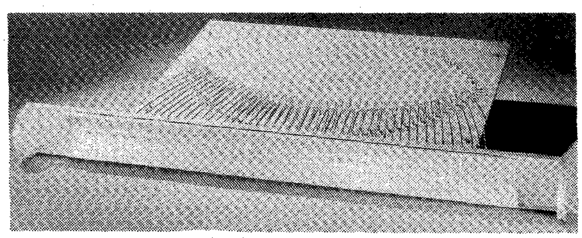

Fig. 14. Construction of lens antenna.

The construction of the azimuth and elevation phased arrays is shown in Fig. 8. The 1° azimuth array has 104 slotted waveguide elements in a 12-ft aperture, fed with a stripline power divider. The phase shifter connects directly to the stripline divider and radiating elements, thus eliminating the need for coaxial cables. The 1° elevation array has 82 dipole elements in a 12-ft aperture. A photograph of the elevation array is given in Fig. 9. Measured patterns on this array are shown in Fig. 10 for some of the coarse-scan increments.

The phased array, being a parallel system, has the inherent advantage that it is a "fail soft" unit. Field-measured data show that 20 percent of the total phase-shifter bits, when randomly failed, still allow satisfactory array operation.

Lens Array—1.5–3.0° Beamwidth

The lens array concept is illustrated in Fig. 11. The lens design uses the theory presented by Rotman and Turner in 1963 [1]. The lens consists of a parallel plate air dielectric section, a group of lens coaxial cables (one to each element in the array aperture), and a commutation scan network. The lens concept is used with both azimuth and elevation scanners. Beams at various angles in space are generated, corresponding to the input probe excited. For example, if a probe at the center of the input probe focal arc is excited (position no. 1), a plane wave, with uniform illumination, is generated at the aperture plane corresponding to boresight beam no. 1. If a probe around the input focal arc (position no. 2) is excited, a new phase gradient is produced, and beam no. 2 is generated at a new angle in space. Likewise, a probe excited at position no. 3 will generate still another beam at angle no. 3, etc. Lens input probe spacing corresponds approximately to 1-beamwidth spacing. To provide a cosine illumination function for sidelobe control and a means of fine-scan scanning (generating beams corresponding to positions between input probes), a group of three input probes is excited with a precise set of amplitude weights. The beam is scanned in 0.1-beamwidth increments by commutating this set of amplitude weights around the input probe arc. The number of beamwidths scanned is controlled by the number of input probes on the focal arc. The lens has three perfect focal points, and the design is generally such that one is at boresight and one each at the plus and minus scan limits. Phase aberations between focal points cause pointing errors which are compensated for in the beam steering unit. Lens antennas have been implemented with scan angles from ±10 to ±40°.

The scan network for a 1.5° beamwidth antenna with 15° scan is shown in more detail in Fig. 12. Sixteen coaxial cables and four SP4T diode switches interconnect the 16 lens input probes to the four fine-scan modulator outputs. The fine-scan modulator generates ten sets of fine-scan

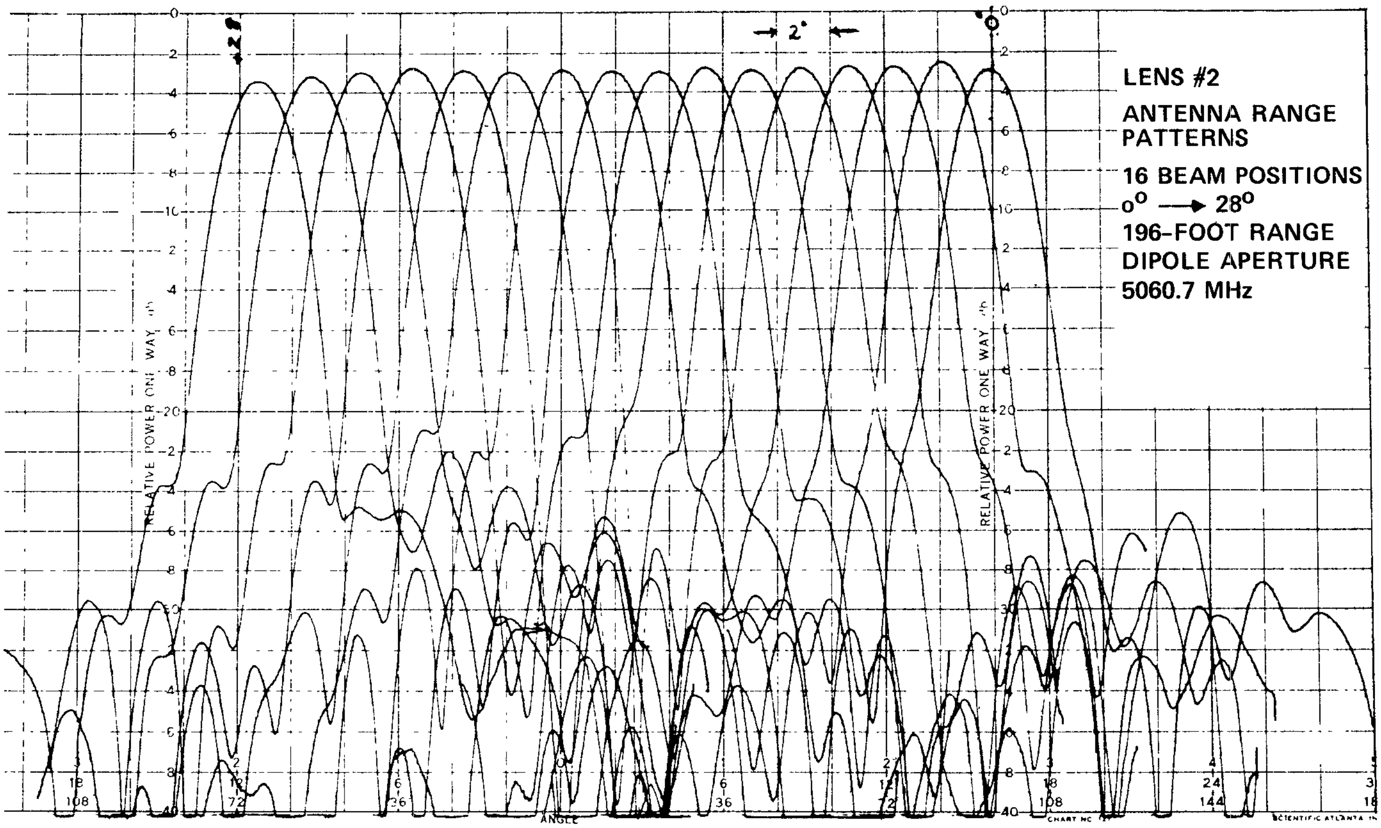

Fig. 15. Lens antenna measured patterns.

weights, resulting in ten increments between probe positions, and fine-scan steps of approximately 0.1 beamwidth. The diode switches commutate these weights over the 16 input lens probes. The scan process is as follows: With the switches all in position no. 1, lens probes no. 1 through no. 4 are excited with the first set of amplitude weights, resulting in a beam corresponding to the position of probe no. 2. With the fifth set of weights, equal amplitude is applied to probes no. 2 and no. 3, resulting in a beam midway between the probes. With weight set no. 10, the beam position corresponds to probe position no. 3. At this point, switch no. 1 is switched to port no. 2, resulting in excitation of lens probes no. 2 through no. 5 and the fine-scan modulator sequence repeats. This process continues across all the lens input probes, resulting in the beam scanning in 0.1-beamwidth increments at a rate of 20000 °/s. Each fine-scan increment is $\approx 7\ \mu s$.

A computed beam-pointing error curve for a 2° lens array antenna for a 40° scan is shown in Fig. 13. The heavy curve with the bow shows the effect of phase aberration errors before correction with the beam steering unit. Note the absence of error at the focal points (boresight and 40°). The oscillating curve was computed using the actual measured weights from the fine-scan modulator. The dashed curve shows the allotted error for this 2° antenna.

Fig. 14 shows the construction of the 2° lens antenna. This antenna has a dipole radiating aperture consisting of 46 elements extending 6 ft. The parallel plate lens is 3 by 4 ft by 1 in thick, and has 46 output probes and 34 input probes. The lens cables are 0.141-in semirigid coaxial cables cut to specific lengths. The measured patterns on this antenna are shown in Fig. 15. These patterns were measured with two-probe excitation on the lens input. As shown, there is very little amplitude variation with scan, and the average sidelobe level is 20 dB down.

Summary

A system overview of a microwave landing system satisfying the entire spectrum of users has been described. Ground hardware implementations to overcome the environmental problems encountered at airports have been discussed. Two classes of scanning beam array antennas have been designed and evaluated. Each class of antenna has performance and cost merits depending on the application. All aspects of the designs presented have been field tested, or are now in the process of field tests.

References

[1] W. Rotman and R. F. Turner, "Wide angle microwave lens for line source applications," *IEEE Trans. Antennas Propagat.*, pp. 623–632, Nov. 1963.