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94 GHz MMW Imaging Radar System

Yair Alon and Lon Ulmer
Lear Astronics Corporation

ABSTRACT

The 94 GHz MMW airborne radar system that provides a runway image in adverse weather conditions is now undergoing tests at Wright-Patterson Air Force Base (WPAFB). This system, which consists of a solid state FMCW transceiver, antenna and digital signal processor, has an update rate of 10 times per second, 0.35° azimuth resolution and up to 3.5 meter range resolution. The radar B scope (range versus azimuth) image, once converted to C scope (elevation versus azimuth), is compatible with the standard TV presentation and can be displayed on the Head Up Display (HUD) or Head Down Display (HDD) to aid the pilot during landing and takeoff in limited visibility conditions.

INTRODUCTION

The technology now exists to take the next step in all-weather landing capability. An Enhanced Vision System employing a weather penetrating sensor interfaced to a raster/stroke heads-up-display will give the pilot an out-the-window view of the runway which allows a "VFR" manually flown approach in CAT III weather conditions at facilities that have only CAT I quality precision or non-precision approach guidance. This provides several advantages over conventional autoland operations:

- Potentially autonomous CAT IIIa or IIIb operation on any runway
- Ground movement at any RVR
- Takeoff at 300 ft RVR at any facility
- Runway incursion detection
- Reduced approach spacing — "VFR operations"

The final system configuration is illustrated in Figure 1. It consists of a scanned antenna, solid state TX/RX, DSP, radar controller and HUD.

EVS TESTBED

An EVS testbed has been developed by Lear Astronics Corp. under a joint FAA/Air Force contract in order to evaluate quantitatively the performance of a 94 GHz FMCW imaging radar in real weather conditions.

The testbed depicted in Figure 2 is being evaluated in a stationary tower test at Wright-Patterson AFB starting in August of 1991, and will then be integrated into a Gulfstream II business class jet for flight testing in adverse weather conditions during 1992.

The testbed consists of a 94 GHz tilt-scanner antenna, a solid state transceiver, a radar interface unit, a digital signal processor, and an integral radar/video data recording system. The antenna with its drive electronics, the TX/RX, and the radar interface unit will mount in the radome of the GII, and the DSP and data recording equipment will be rack-mounted in the cabin.

OPERATIONAL RADAR REQUIREMENTS

The results of a trade-off study to establish radar performance requirements are summarized in Table I.

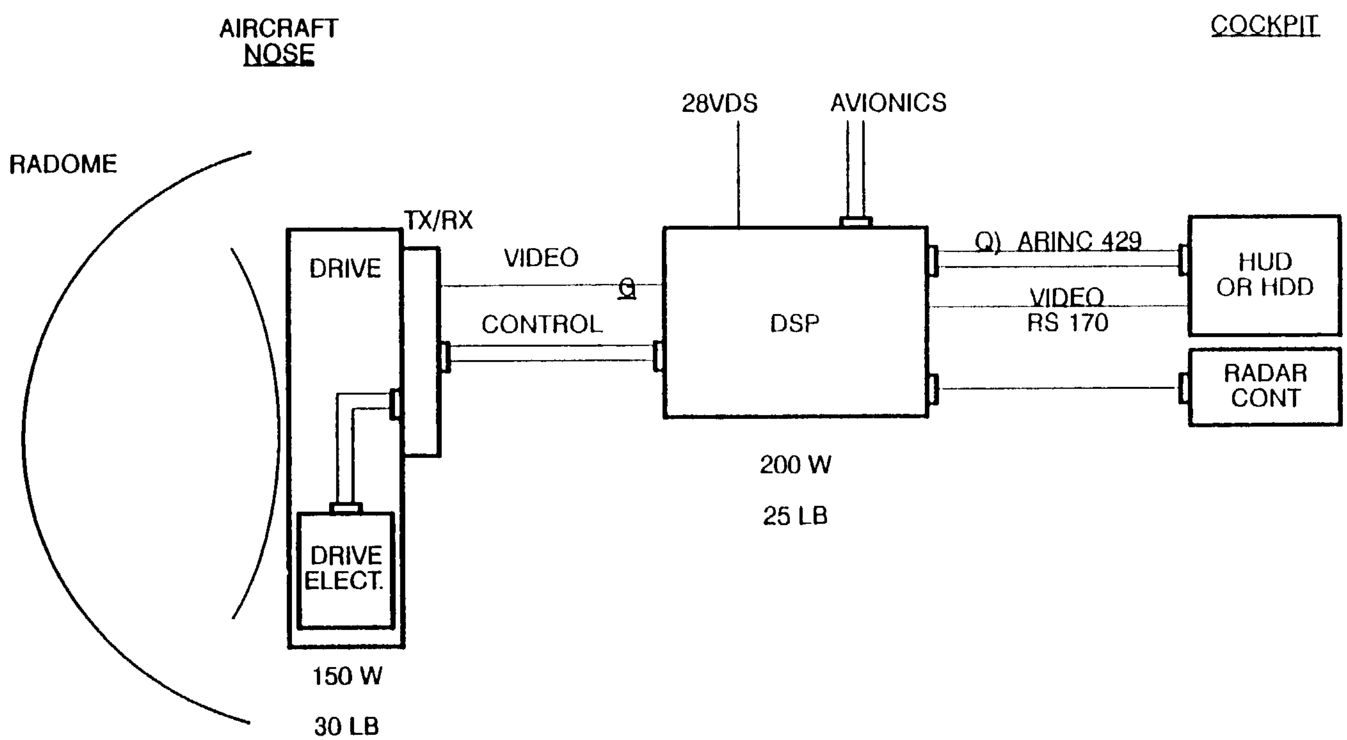

Figure 1. Final Production System Equipment Rack

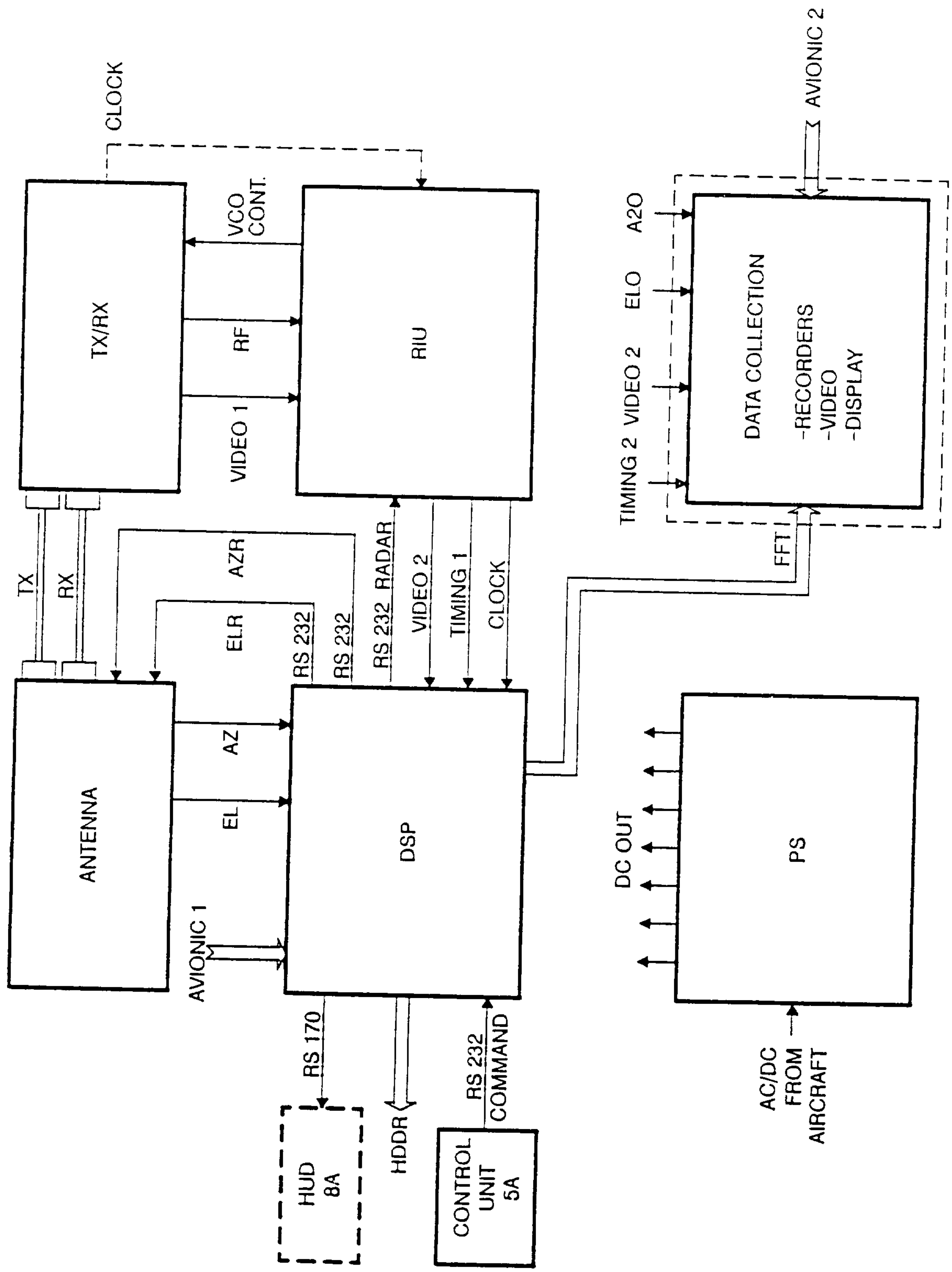

Figure 2. Basic Configuration

Table I. Operational Requirements Summary

RADAR OPERATIONAL SPECIFICATIONS

- Display – C scope (elevation versus azimuth)
- Maximum Processed Range – 6,000 meter, acquisition mode; 3,000 meter, approach mode; 1,500 meter, taxi mode
  - The acquisition mode is for runway detection and ground map display.
  - Approach mode is selected during the final phase of the landing process (range to runway threshold less than 2,000 meters).
  - Taxi mode is selected during aircraft taxi and takeoff.
- Mode Change – Automatic or manual
- Update Rate – 10 times per second
  - Radar antenna horizontal scan of 10 times per second (5 Hertz) is utilized.
- Scan Angle in Azimuth – ± 15 degrees
  - The horizontal scan covers the total HUD field of view, 30 degrees.
- Elevation Stabilization – ± 15 degrees
  - Adjustment to compensate for aircraft pitch changes to maintain optimum runway illumination.
- Elevation Rate – 30 degrees/second
- Azimuth Resolution – 0.35 degree (5.4 milliradian)
  - Two way antenna azimuth beamwidth.
- Range Resolution – 14 meters for 6,000 meter range, acquisition mode; 7 meters for 3,000 meter range, approach mode; 3.5 meters for 1,500 meter range, taxi mode
- Azimuth Accuracy – 0.3 degree
  - Azimuth pointing accuracy of 5 meters at 1,000 meters from runway.
- Elevation Accuracy – 0.3 degree
  - Accuracy is affected by altitude and roll data avionic input.

For nonprecision approaches and autonomous OPs the radar must allow the pilot to detect, acquire, and track the SVS scene prior to the Visual Descent Point (VDP), which requires a processed range of about 3000m. A horizontal scan rate of 10X/sec (5 Hz antenna rate) was selected to minimize scene latency. The capability of further extrapolating the scene, using the aircraft state vector to "smooth" the image and decrease scene flicker, has also been incorporated in the system and software design. (Eventually, it may be desirable to slow the actual antenna scan to be compatible with X-band rate to as low as 1 Hz weather radars.)

The azimuth scan angle of ± 15 degrees was selected to make the scanned scene compatible with typical HUD azimuth fields-of-view. This permits the crew to "see" the runway on the HUD under required cross wind conditions. The antenna is pitch stabilized with a range of $\pm 15°$ to maintain optimum runway illumination in all radar modes and flight path angles.

An azimuth resolution of 0.35 degree was selected as the minimum resolution required to provide the crew an adequate image. This number directly affects the antenna size, hence is an important design parameter that should be verified through simulation and flight test. If larger azimuth resolutions can be tolerated a smaller antenna can be used which would simplify the radome integration problem.

EVS SENSOR TECHNOLOGIES

A 94 GHz FMCW was selected from potential EVS sensors including FLIR, active 35 GHz radar, and a passive 94 GHz radiometer. It was felt that the 94 GHz radar was a mature technology that provided the best overall operational capabilities in low visibility when compared to the other sensors.

FLIR was eliminated as a technology due to poor performance in fog. The extinction coefficient of IR in fog is too large to meet the range requirements of an EVS sensor. The IR sensor may have an application in the taxi mode where the high resolution, TV-like image of the FLIR may be desirable for ground movement and where the visual range requirements are not so demanding.

The most decisive factor in choosing the 94 GHz active radar technology over 35 GHz radar is that the 94 GHz radar yields much better azimuth resolution for a given aperture. To achieve the required 0.35 degree azimuth resolution the 94 GHz radar allows a much smaller antenna size that easily fits into the form factor of existing radomes. The EVS testbed uses a 24 inch antenna. To obtain the same resolution from a 35 GHz radar would require a 64 inch antenna without using some advanced processing technology such as "super-resolution."

Although the 35 GHz radar provides better meteorological parameters, as can be seen in Table II, these only come into play at ranges beyond what is operationally required for EVS. For the ranges of interest, the 94 GHz penetrates the weather adequately, meets the azimuth resolution requirements with a workable size antenna, and is a mature technology at the required transmitted power levels (< 1 watt).

The Frequency Modulated Continuous Wave (FMCW) selected utilizes the change in frequency to resolve target range. The transmitted signal is swept over a wide frequency range in linear form. The received signal, when mixed with a portion of the transmitter waveform, will produce a beat frequency proportional to the delay introduced by the target range. In the approach mode, the EVS transmitter sweeps 100 MHz within 1.8 msec; this is equivalent to 370.37 Hz for each 1 meter delay.

ANTENNA

The 24" x 8" Flat Parabolic Surfaces (FLAPS) scanning reflector antenna was developed by Malibu Research Associates for the EVS testbed (Figure 3).

This technology is designed such that a flat surface behaves electromagnetically as if it were a shaped reflector. A FLAPS surface is essentially a single large printed circuit board. The feed is fixed and only the lightweight reflector scans ±7.5 degrees. The antenna produces a 2:1 scan enhancement, which gives a ±15 degree field-of-view. The FLAPS surface focuses the beam, converts from linear to circular polarization, and forms the $COSEC^2$ elevation shaped beam.

The TX/RX is mounted integrally to the antenna assembly behind the reflector surfaces to minimize waveguide losses. The antenna is scanned at 5 Hz (10X through center), in azimuth, and can be pitch stabilized under computer control through a pitch gimbal that has ±15 degree authority.

RADAR TRANSCEIVER

The 94 GHz solid state FMCW linearized transceiver developed by Marconi Defence Systems, depicted in Figure 4, consists of two LRUs, the RF unit (TX/RX) mounted directly on the antenna and the Radar Interface Unit (RIU) colocated with it. The radar transmitter uses a phase lock loop linearized VCO and an Injection Locked Oscillator (ILO) to produce the 400 mW output power. The received signal is downconverted by an MIC assembly to baseband and then amplified by a digitally gain controlled amplifier stage to produce the frequency/range related signal. The conversion from frequency to range is performed in the system Digital Signal Processor (DSP).

Table II. Meteorological Parameters			
PARAMETER	35 GHz	94 GHz	REMARKS
Attenuation dB/km One Way			
Clear Air	0.12	0.4	
Fog 0.2 gm/m	0.15	0.8	
Rain 5 mm/hr	1.1	4.0	
Rain 10 mm/hr	3	6.3	
Snow 2.5 mm/hr	0.3	1.46	Dry Snow
Backscatter, Circular Polarization Volumetric Clutter (m^2/M^3) x $10^{(-4)}$			
Fog 0.2 gm/m	–	–	
Rain 5 mm/hr	0.063	0.25	
Rain 10 mm/hr	0.19	0.44	
Reflectivity (dB) 3 Degree Grazing Angle			
Grass (Dry)	-24	-18	
Concrete	< -35	< -30	
Snow (Dry)	-18	-13	
Snow (Wet)	-28	-18	

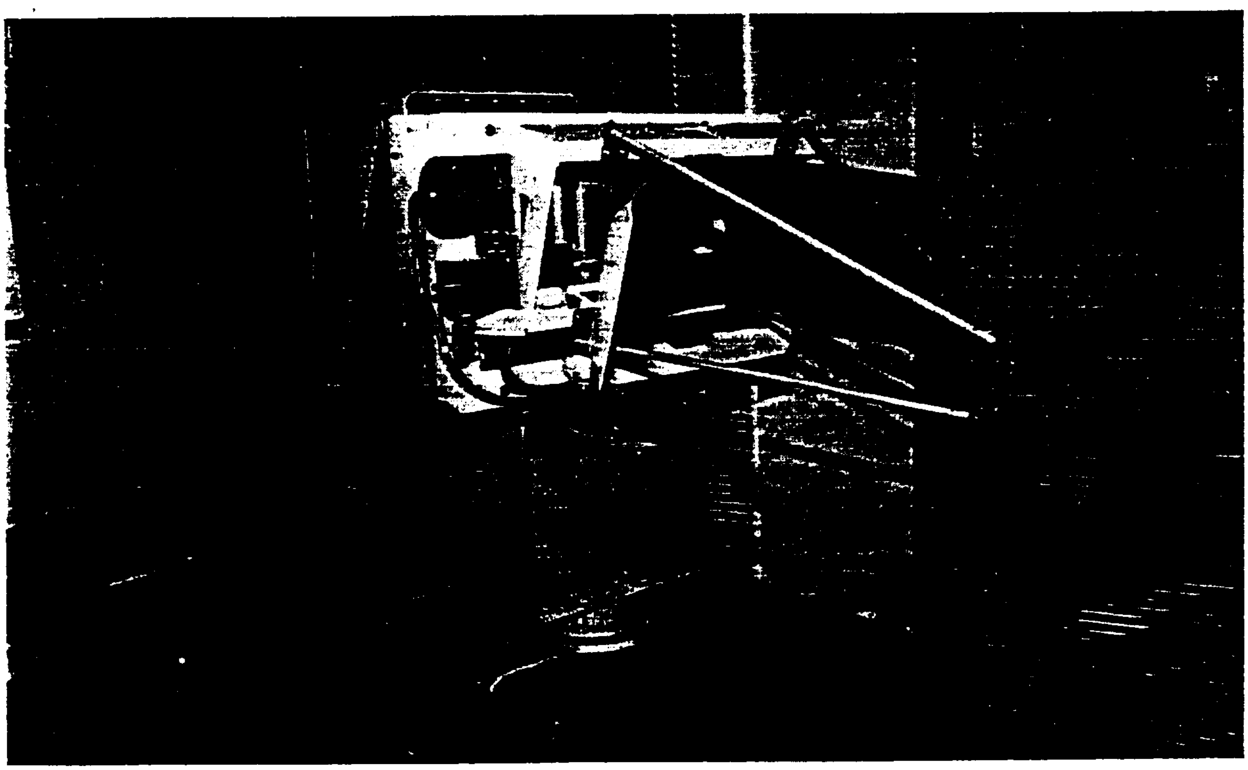

Figure 3. The 24" x 8" Flat Parabolic Surface (FLAPS) Scanning Reflector Antenna

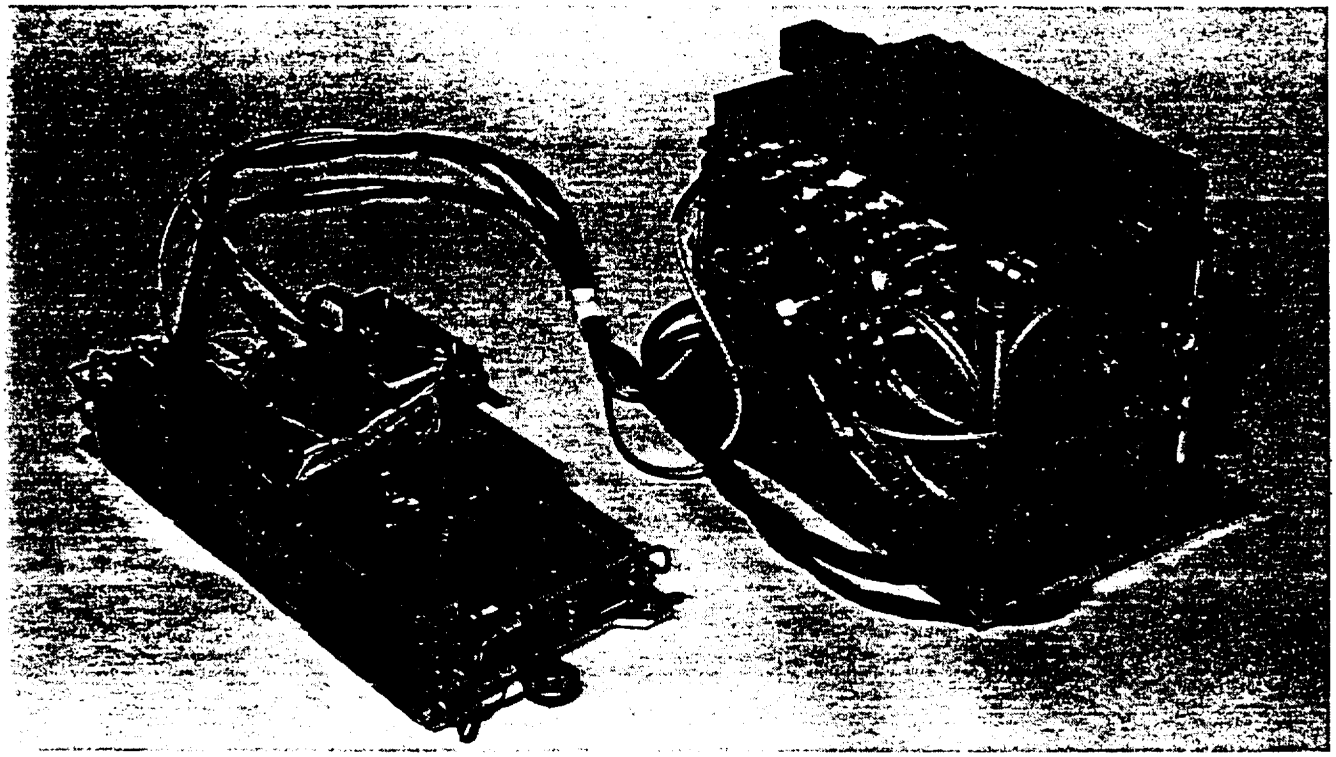

Figure 4. TX/RX Assembly

DIGITAL SIGNAL PROCESSING UNIT (DSPU)

The DSPU, depicted in Figure 5, consists of a fast (400 μsec conversion time) FFT card, a scan converter, and six RISC architecture MIPS R3000 processor/memory card pairs in a single chassis.

The DSP's primary function is to process a radar return signal and convert it to a displayable picture of the runway scene. The radar return input is digitized and stepped through an FFT calculation, creating 256 range profiles per scene, each consisting of 512 range bins. Each range profile is processed individually to enhance the scene definition. Scenes are processed at a rate of 10 per second. The standard radar B scope (range versus azimuth) is converted, in real time, to C scope (elevation versus azimuth display).

After processing, the range profiles are collected in the scene memory space of the scan converter. Motion compensation of the scene for changes in aircraft attitude may be performed before data conversion to RS-170 output format. Scene update to the display is at a rate of 30 per second.

The DSP functions include the following:

- Radar return digitization and FFT processing
- Range profile processing
- Scan conversion with motion compensation
- Command and control interface to operator console
- Command and data interface to radar unit
- Data interface to aircraft avionics
- Image enhancement (Level II software)

TEST RESULTS

Starting in May 1991, the radar system was tested in several locations and runway images were collected for evaluation. Since none of the locations has the required 3° glide slope, or the position toward the runway is to the side, the image evaluation is somewhat limited.

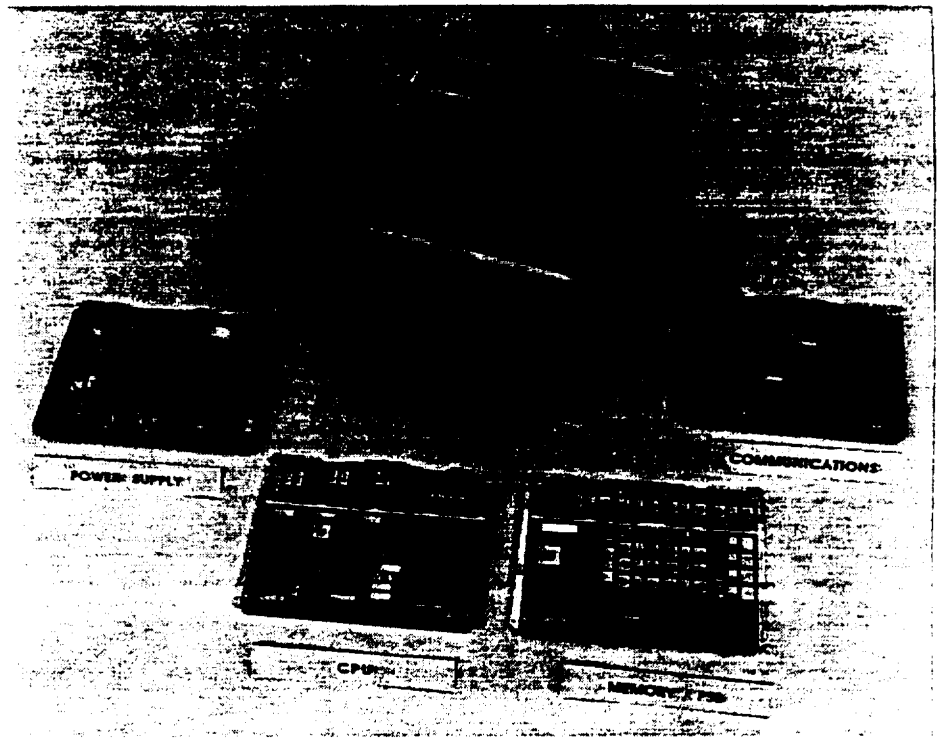

Figure 5. EVS DSPU

Figure 6 illustrates the runway detection from 90° to the side at a very shallow angle (<1°). Runway detection prior to touchdown is presented in Figure 7. The runway at a distance of 2,000 to 3,000m is presented in Figure 8. The dark area in front of the runway is the result of the shadow caused by the tree line.

The effect of the DSPU image processing is illustrated in Figure 9. The raw B scope image presented in Figure 9A is converted to C scope (Figure 9B); the image is then smoothed (Figure 9C) and further processed (Figure 9D).

CONCLUSION

The 94 GHz MMW radar system, now being tested at WPAFB, provides a real time runway image up to a distance of 3 km. The runway can be easily discriminated from the grass surrounding it. Utilizing image processing techniques, the image quality can be further enhanced for a clear HUD runway presentation.

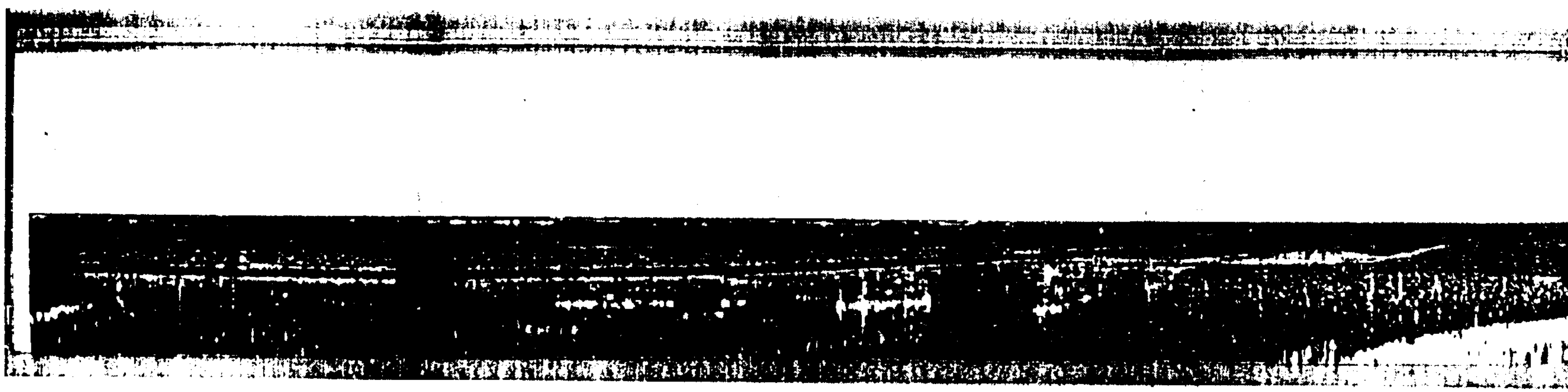

Figure 6. Runway at 90°

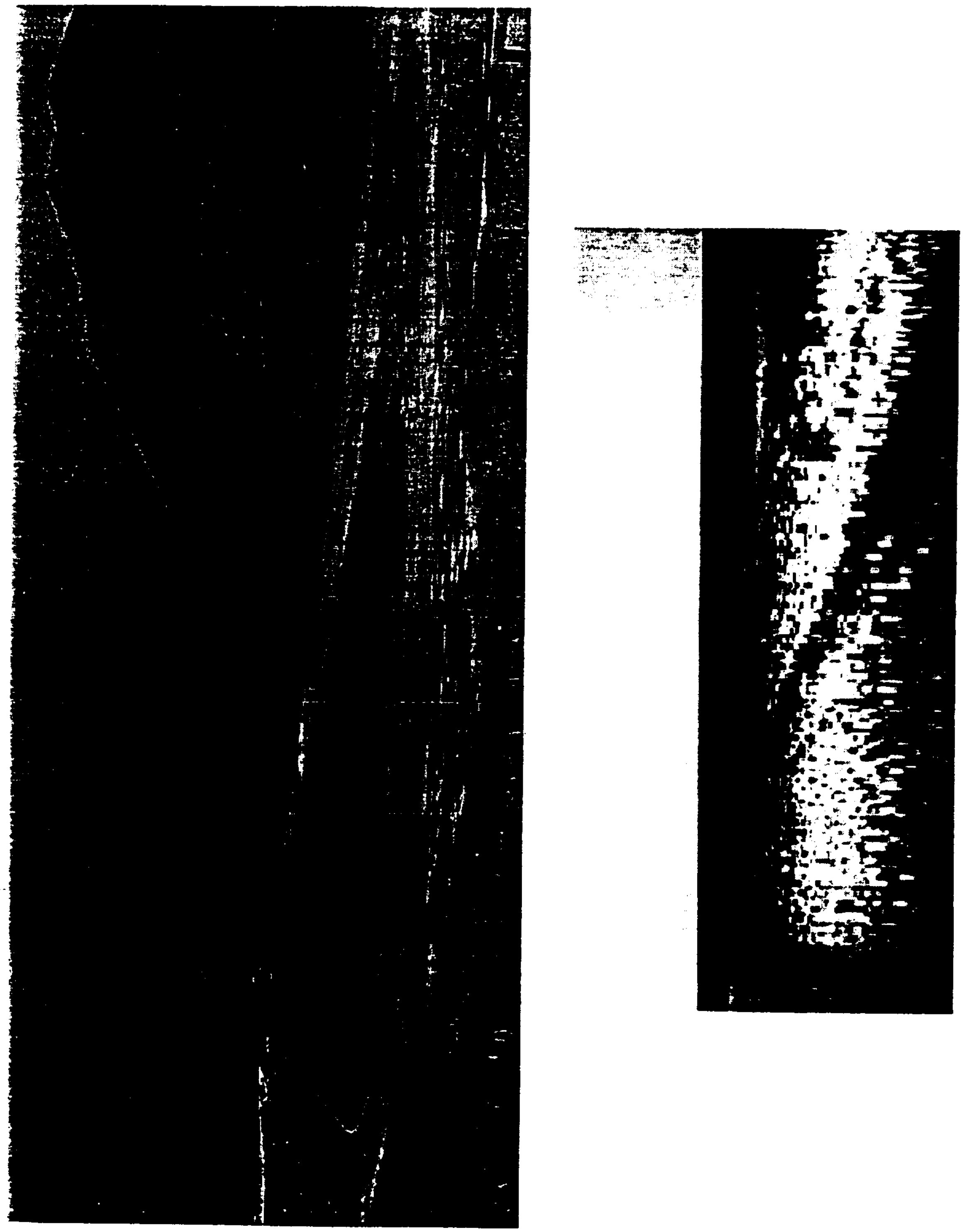

Figure 7. Runway at Short Distance

Figure 8. Runway Image, WPAFB

Figure 9A. B Scope Image

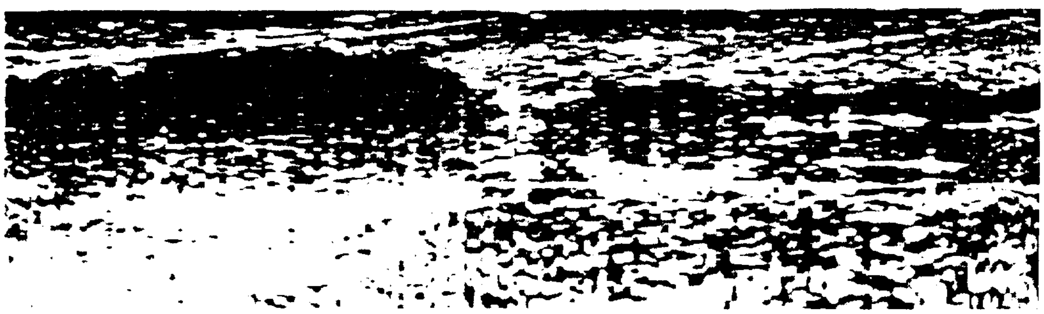

Figure 9B. C Scope Image

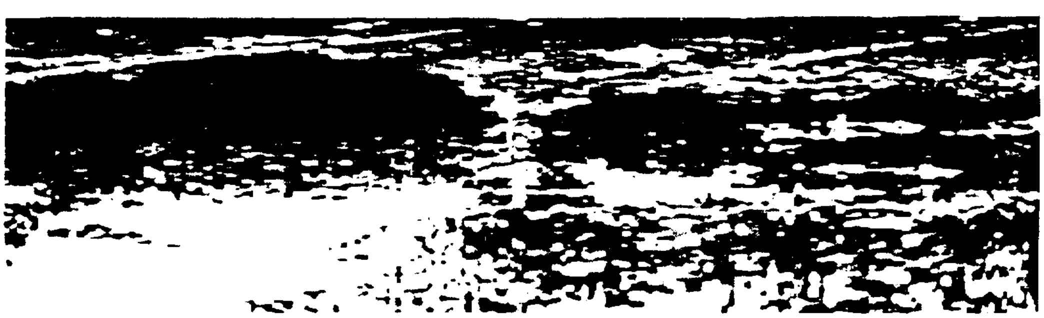

Figure 9C. Processed C Scope Image

Figure 9D. Cluster Process C Scope Image