AIRBORNE RADAR SIMULATION

By

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Abstract

Airborne Radar Simulation, in the present context, is the real-time generation of radar displays and other radar outputs, such as data exchanges with the flight computer or other avionics subsystems, consistent with the actual radar and in response to the interaction with the operator, ownship, targets, and the environment.

The application is flight simulators for man-in-the-loop training of pilots and radar operators, and engineering research simulators for designing radars, avionics systems, and cockpits. Engineering research simulators are frequently used to aid integration and so may incorporate additional aircraft hardware. Otherwise, the requirements are similar to flight simulators. This paper addresses the Airborne Radar Simulator for flight simulator application. The focus is Air-To-Ground radar modes and thus the Digital Radar Landmass Simulator (DRLMS). Keywords: DRLMS, flight simulator, modeling, radar, remote sensing, simulator, training.

1. Introduction

We make a distinction between Air-to-Air (A/A), Air-to-Ground (A/G), and Air-to-Surface (A/S) modes of operation because Airborne Radar Simulator implementations are often quite different for each of these missions.

A/A Radar Modes—

Typically require complex models for radar detection, tracking, and recognition, but processing throughput and memory requirements are modest, and normally no landmass, other than possibly a homogeneous landmass, is required.

A/S Radar Modes—

Principally ocean surveillance modes. The primary application is the detection, tracking, and recognition (imaging) of ocean surface targets. The landmass, if required, may be two- or three-dimensional with minimal fidelity and possibly just include shoreline.

A/G Radar Modes—

Require a landmass and frequently a weathermass, and represent the biggest challenge to the radar simulation engineer, resulting in the implementation of the Digital Radar Landmass Simulator (DRLMS).

This paper addresses the current state-of-the-art DRLMS, database architectures, and databases for the primary A/G radar modes. These modes include:

- Conventional ground mapping such as Real Beam Ground Map (RBGM) modes.
- Coherent ground mapping such as Doppler Beam Sharpening (DBS) and Synthetic Aperture Radar (SAR) modes.
- Search and track such as Ground Moving Target Indication (GMTI) and Ground Moving Target Track (GMTT) modes.
- Navigation such as Terrain Following and Terrain Avoidance (TF/TA) modes.

2. Evolution Of The DRLMS

One of the earliest radar simulators was built by R. K. Moore at the University of Kansas in the late 1950's.[1] It was an acoustic simulation that used a water tank and piezoelectric transducers to replicate the transmission, delay, reflection, and reception of the radar signal. A representative radar range trace could be achieved. This device was useful for engineering research and as an aid in radar systems design.

By the mid-1960's, glass plates with flying spot scanners were routinely used to generate reasonably good radar displays. The glass plate was a photographic positive of the desired radar image of the gaming area. It was backlit with a uniform light source while a photodiode was rapidly scanned on the front side, producing a voltage proportional to the radar return. Unfortunately, this system had numerous shortcomings, including lack of compensation for occulting with changes in aircraft altitude.

Terrain boards were used in the 1970's. A vertical video probe was placed at the appropriate location and a directional light source was positioned according to the encounter geometry. The light source illuminated the monochrome-colored terrain in a manner that created pseudo-radar imagery with fairly accurate radar shadows. The system worked, but was somewhat cumbersome and inflexible.

Neither the flying spot scanner nor the terrain board produced an accurate depiction of angle resolution effects.

Another difficulty with early DRLMS was the lack of adequate source data from which to build the landmass database. This problem was abated in the early 1970's with the introduction of the Defense Mapping Agency (DMA) Digital Landmass System (DLMS), the forerunner of the modern Digital Terrain Elevation Data (DTED) and Digital Feature Analysis Data (DFAD). Soon this database was finding application.[2] Several DRLMS were built, and by 1980 their construction was routine. These were hardware-intensive implementations of the radar models comprised of 800–900 printed circuit boards stuffed to the gills with small-scale integrated circuits (e.g., the GE F-16 DRLMS). Suffice it to say, they were big, expensive, and nontrivial to maintain.

By the mid-1980's, several DRLMS were built with minicomputer front-ends and array processor back-ends. Examples include the B-1 DRLMS built by Cubic and Boeing. These systems shared many of the undesirable characteristics of the predecessors.

In 1985, we developed a new approach to building DRLMS: a software-only solution using a high-speed, general-purpose computer constructed of monoboard computers on a VMEbus. This proved to be successful, and as computers, memory, disk drives, etc. have improved, so has this approach to building the DRLMS. Thus Camber has become the leading DRLMS manufacturer.

By 1990, general-purpose workstations became a powerful enough computing resource to replace the VME system, and UNIX SVR4 arrived, providing a means for running realtime UNIX. So we migrated to Silicon Graphics, Incorporated (SGI) computers and are building DRLMS with them today. The Indian Navy Sea Harrier flight simulator is currently being upgraded and will soon be fitted with an SGI-based DRLMS for the Blue Fox Radar.

3. A Typical Radar

Figure 1 provides a block diagram of an A/G radar. Table 1 lists the basic radar characteristics. Note that this information is generic and not specific to any particular radar, but is typical of a modern A/G radar.

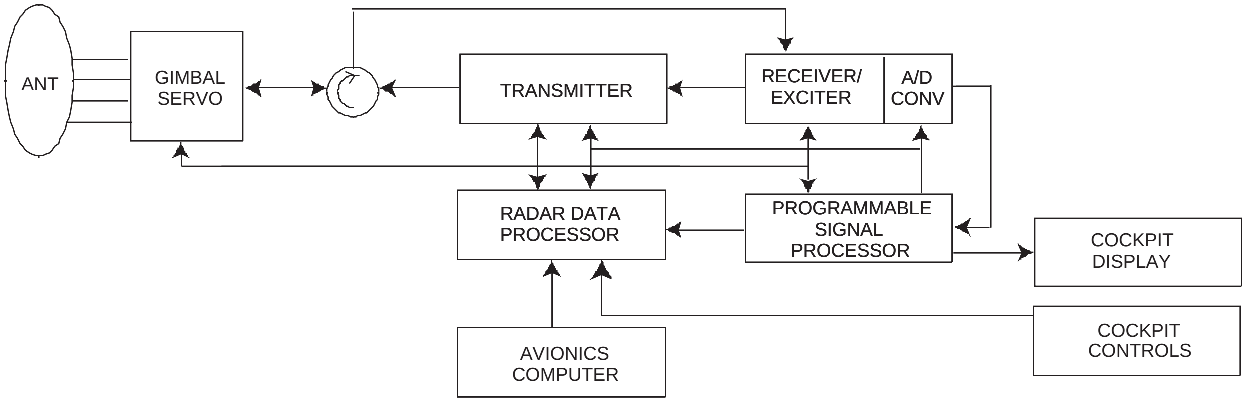

Figure 1. Radar Block Diagram

Table 1. Typical A/G Radar Characteristics.

Frequency: 10GHz, X-Band
Antenna: Flat Plate, 3 deg x 3 deg Beamwidth, 30 dB Gain, -30 dB Sidelobes
Transmitter: Traveling Wave Tube (TWT), 2KW Peak Power, 5% Duty Cycle for A/G modes
Receiver: 5 dB Noise Figure, Dual Conversion, RF Preamp, STC, AGC
A/D Conversion: I/Q, 8 Bits, 25MHz Maximum Rate
PSP: 25 MFLOPs, 2Mbytes RAM
RDP: 2.5 MIPs, 64Kbytes RAM
Communications: 1553 Bus
Display: 256 x 256 x 8 Bits, Monochrome, Raster
Exciter: 13:1 Barker Code Pulse Compression, Variable Chip Rate, 0.1 µsec min, 10µsec max

The radar contains a Radar Data Processor (RDP) and a Programmable Signal Processor (PSP). The RDP provides control of all the radar functions, tracking, motion compensation, and communications to the avionics computer. The PSP provides predetection and postdetection signal processing, display processing, range/azimuth compression, and other high-speed processing.

The exciter creates the modulated waveform that is amplified by the transmitter and radiated into space by the antenna. The A/D converter translates the receiver output from analog to digital for PSP processing. The gimbal servo unit is driven by the RDP and maintains antenna scan and stabilization.

Table 2 lists the three primary radar modes. The RBGM mode is a conventional radar mode. The only distinction is that with modern technology it is possible to match the radar resolution to the display resolution by variable pulse compression, and thus eliminate the collapsing losses present in earlier radars. The DBS mode is a scanning mode, providing constant azimuth resolution throughout the field of regard. It is generated by sequential batch processing of short, fixed-length FFTs performed at a variable PRF and combined (as adjacent segments) to give the continuous scan display. The SAR mode is a spotlight mode, providing constant cross-range resolution at any designated range/azimuth location. It is generated by a single, long FFT that is performed with motion compensation at a constant PRF. (In reality, several FFTs are used to provide adequate azimuth coverage and several looks, performed at different RF frequencies, are noncoherently combined to improve image quality.)

Both DBS and SAR modes require motion compensation. The aircraft motion is acquired from the inertial navigation system. Then the receiver Local Oscillator (LO) is offset by appropriate frequency to remove the instantaneous Line-Of-Sight doppler from the radar signal that is due to the aircraft motion.

Table 2. Typical A/G Radar Mode Parameters.

PARAMETER	RBGM	DBS	SAR
Azimuth			
• Center	Heading Stabilized	Selectable, +/– 60 deg	Selectable, +/– 60 deg
• Swath	+/– 60 deg (max)	45 deg	2.5nmi x 2.5nmi
• Scan Rate	60 deg/sec	Varies with Azimuth 60 deg/sec to 5 deg/sec	Spotlight Mode
• Resolution	Realbeam	20:1 Beamsharpening, 0.15 deg	50 ft cross-range resolution.
• Other		+/– 5 deg blind zone 256 Azimuth Bins	256 Azimuth Bins
Range			
• Scale	Selectable, 5 – 160 nmi	Selectable, 5 – 40 nmi	Range/Azimuth Center is Designated.
• Resolution	$R_{max}/256$; 950 ft for 40nmi	$\Delta R = R_c \Delta Az$; 650 ft for 30 nmi	50 ft. 256 Range Bins.
Miscellaneous			
	PRF = 2KHz P – P Frequency Agility	Variable PRF, 2.5KHz – 500Hz to give required CPI at each azimuth. CPI = 25msec – 150msec.	Variable PRF 1.5KHz–3KHz. PRF = 1700Hz at 30 deg, 25nmi, 300kts. CPI varies with range, azimuth, aircraft velocity.
Signal Processing			
	STC, AGC, NCH Int.	32-Point FFT	256-Point FFT, 2 – 4 Presum, 1, 2, 4 Multi-look.
Display Format			
	Offset PPI	Offset PPI	Plan View, Heading Up

4. The Technical Challenges

The radar described above possesses typical radar parameters and processing and provides a basis for discussion. However, an actual production radar will have dozens of modes, submodes, and functions. It is not unusual to have ten or more display formats with significant radar-generated symbology and overlays for each display. It is not unusual to have 100 or more user-selectable radar parameter values.

Most of this complexity is due to the great amount of design flexibility afforded by the introduction of the RDP and PSP into the radar about 20 years ago. All of the above represents added complexity to the DRLMS, but is not truly a technical challenge. The major technical challenges are:

- Large area coverage for the RBGM mode.
- Variable range resolution for the coherent ground map modes.
- Fidelity for the high resolution modes.

Our approach to meeting these challenges is discussed next.

5. Functional Overview Of The DRLMS

Figure 2 provides a functional block diagram of the radar model employed by the DRLMS. The modeling technique employed by a radar simulator is an important component in producing a realistic radar display. Only through a comprehensive understanding of the underlying principles and theories of radar systems engineering is it possible to provide realistic simulation suitable for training. The modeling approach incorporates a detailed database and a realistic treatment of the interaction of the simulated radar model with the terrain, water, weather, and targets. All appropriate radar phenomena and effects are accounted for. Figure 2 indicates the primary functional elements of the simulated radar and environment. The environment model provides the gaming area database to which the radar model is applied. The rest of the radar model can be partitioned in much the same way as the actual radar. It consists of an antenna, transmitter, receiver, a signal processor, and interfaces to other systems such as the display system.

5.1 Environment

Terrain and weather are represented by three-dimensional and four-dimensional databases. The terrain is described by topography, radar reflectivity, and surface attributes. The topography consists of a 2-D grid of elevations or a list of polygon vertices; the grid is best for applying the radar model, the polygons are best for storage and for representing varying scene densities. The radar reflectivity is provided for each element in the topography and is the radar backscatter coefficient (s_0) for homogenous surfaces and Radar Cross Section (RCS) for specular returns, such as man-made objects. Surface attributes are provided for each element in the topography and include indications of trans-

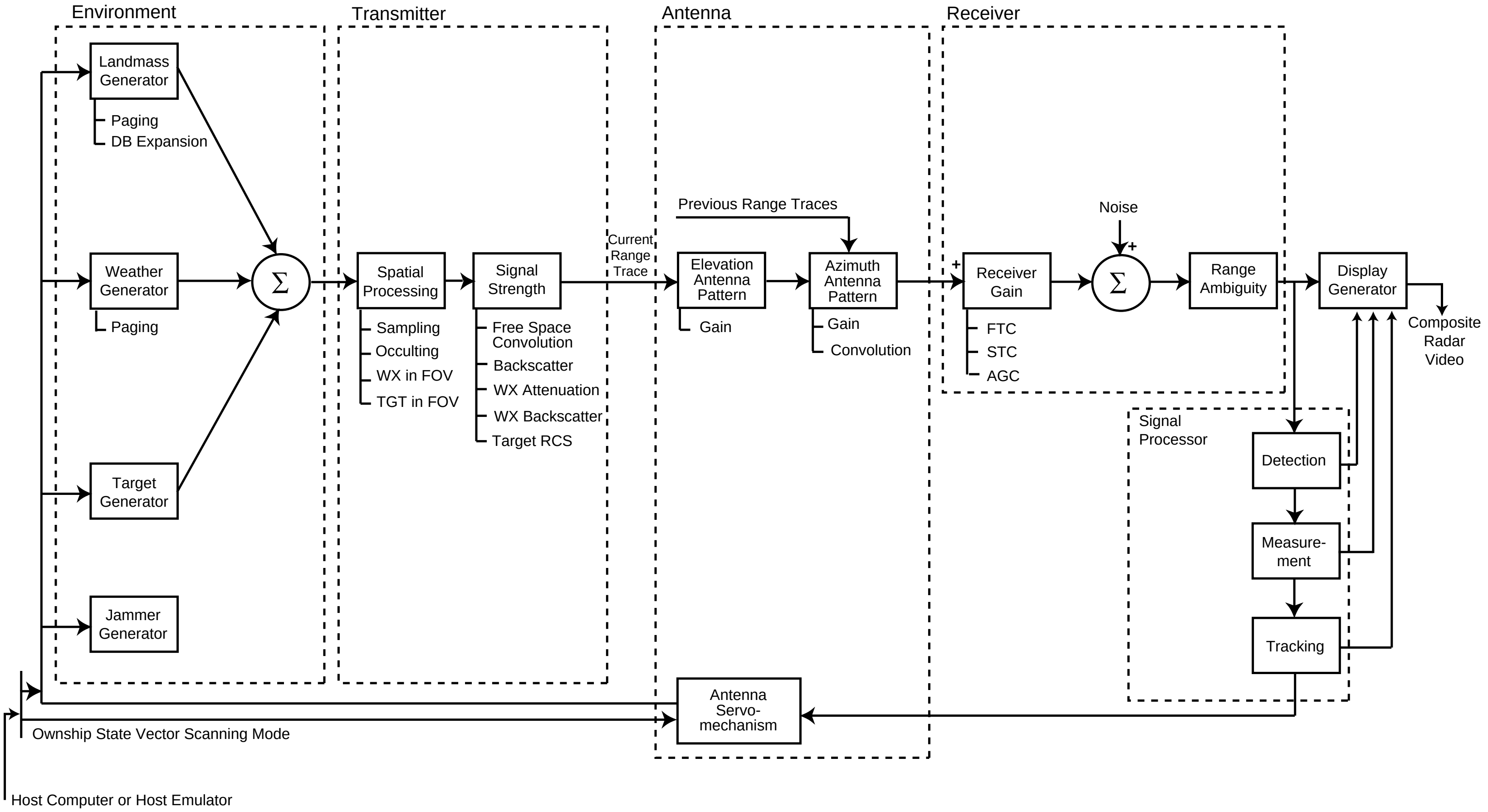

Figure 2. Radar Model Process Flow Diagram

parency (e.g., a powerline tower may have large RCS, but not create a radar shadow), water, shoreline, etc.

The weather is described by a 3-D grid of rainfall rates. The rainfall rate is used to compute the rain's volumetric backscatter coefficient and signal attenuation.

The environment model maintains the database by paging terrain and weather data from disk into memory. Paging is required because the size of the terrain database for the gaming area greatly exceeds available memory. Gaming area databases can be as large as 64Gbytes, while we usually have about 256Mbytes RAM available for local area map storage.

The landmass data is stored on the disk drive in a compressed format. We have devised a method for using a polygonal format for this compression**;** by judicious design this format can be made identical to the Image Generator. Thus, perfect correlation between the radar, visual system and IR systems is achievable since they can utilize the same database.

During runtime, the environment model expands the landmass to a gridded database that is more suitable for radar modeling. For RBGM, a grid for each range resolution (i.e., range scale) is maintained and this process runs as a background task. Frequently, modern radars have variable range resolution that is adjusted to optimize the radar modes based upon range scale selection, etc. For these modes (RBGM expand, DBS, SAR), we perform realtime expansion of the polygonal database into the gridded database with the grid spacing based upon the range resolution.

An important aspect of the polygonal database format is that it can very easily represent scenes of varying content density. For instance, rural areas need only be represented by a few polygons, whereas urban areas, strategic targets, etc., can be represented with many polygons. If we only used a grid, then we would have to design the system based upon a worst-case content density requirement which is not optimal.

5.2 Spatial Processing

The first step in modeling any of the A/G radar modes is to gather the terrain data that is within the radar antenna azimuth beamwidth. This is accomplished by periodically forming range traces at closely spaced azimuth angles.

The range trace azimuth spacing is based on the actual radar antenna beamwidth, scan rate, and pulse repetition frequency.

The range samples are spaced according to the radar range resolution or the radar display resolution. Note that the formation of range traces is area sampling: all data points between range traces are processed to form the range samples on a given range trace to prevent blinking and other simulator anomalies.

Once range trace is computed, the occulting process is applied to the trace to determine shadowing and the grazing angle; Earth's curvature effects are included. The occulting process for targets is essentially the same except the target altitude is introduced. This calculation is performed sequentially, beginning with the near range and proceeding to far range for efficiency and to reduce redundant calculations.

For each sample, the depression angle to the terrain is computed. The grazing angle and reflectivity computed and are used to determine the backscatter coefficient.

5.3 Signal Strength

The total power for each radar range/azimuth bin is determined as the simulated antenna sweeps through the scan volume. Signal power due to terrain, water, weather, jammers, and targets are calculated separately using the radar equation and then combined to derive the received signal strength. These equations determine the radar signal attenuation due to both free-space and atmospheric losses.

The received power due to the terrain is calculated using the radar equation. It is based upon the combination of the backscatter coefficient for diffuse clutter and RCS for discretes. Each terrain sample is computed as a random variable with appropriate distribution (e.g., Rician) and with the computed value of average power.

For each range bin that encounters a non-zero rainfall value along the line-of-sight, both rainfall attenuation and backscatter values are determined by accessing a look-up table indexed on rainfall rate. The volumetric backscatter coefficient is used to calculate the magnitude of the resulting radar return using the appropriate radar equation. The attentuation is applied to the current range bin and cumulatively to following range bins.

The received power due to target returns is calculated using a radar equation. The target's RCS is treated as a discrete and is independent of range.

RCS tables are maintained in the DRLMS for each target type. These tables contain RCS values for each target as a function of aspect angle. In the case of distributed targets, the contributions of all scatterers are summed to form a composite return. Effects of target scintillation are included in the calculations.

The received power due to water is modeled in a manner similar to landmass returns. Water tends to be homogenous and is modeled as a random process. The backscatter coefficient is modeled as a log-normally distributed random variable. The mean backscatter coefficient is a function of the sea state.

5.4 Antenna

The antenna model consists of two main components: an antenna servomechanism model and a model of the antenna beam pattern. The servomechanism model simulates the positioning of the antenna in azimuth and elevation. It accounts for the scan mode, antenna dynamics including the interactions of the drive motors, gimbals, resolvers, and the required coordinate transformations. For each radar mode there is at least one scan pattern. This pattern is specified by the scan generator, which uses an internal real-time clock to periodically determine the commanded antenna position. For instance, the RBGM mode is an azimuth scan. This position is converted to the proper coordinate system that is applied to a control system model for the antenna. The control system model accounts for the antenna drives and inertia. A gimbal model is used to determine the antenna direction of motion and the gimbal limits. A resolver model records the antenna position which forms the feedback loop for the control system. Of course, in some modes the antenna position is commanded by the host.

The antenna beam pattern is modeled in both elevation and azimuth. After the individual returns generated by the environment model and the transmitter model are complete, they are modified by computing the attenuation relative to the antenna peak gain at boresight as a function of elevation angle off boresight.

The antenna azimuth beamwidth is accounted for by convolution of the azimuth antenna pattern with the adjacent range traces. This provides the reduction in cross-range resolution with range for RBGM and DBS modes. The azimuth spacing is selected to provide adequate fidelity and can be as small as the product of the radar Pulse Repetition Interval (PRI) and scan rate and as coarse as the radar dwell (approximately the antenna beamwidth). The azimuth antenna pattern can be adequately modeled with 5 to 7 samples.

5.5 Receiver Model

The antenna model provides an output array of signal powers indexed by range at the dwell rate. In the receiver model, the transmit power, range bin integration, and receiver characteristics are modeled. The range bins are formed by convolving the range ambiguity function with the range samples of each range array. The range ambiguity function is derived from the receiver characteristics and can be adequately modeled with 5 to 7 samples.

Receiver functions such as Sensitivity Time Constant (STC), the Automatic Gain Control (AGC) are also modeled. The STC waveform is modeled as a polynomial in range. The AGC is modeled with a classic AGC control loop carefully adjusted to match the characteristics of the actual radar. In addition, any Constant False Alarm Rate (CFAR) techniques such as Fast Time Constant (FTC) are accounted for.

A noise signal is summed with the radar returns to model the background interference in the receiver frontend. The strength of the noise signal is dependent on the receiver bandwidth, noise figure, etc. Note that the receiver gain affects the signal and may affect the noise depending on where the gain is applied. Random noise signals at the proper strength are computed for each range sample and added to the composite radar signal.

5.6 Scan Conversion

If the DRLMS provides a raster scan output, then scan conversion is performed to convert the polar format range/azimuth signal into a Cartesian format x,y signal. (Scan conversion is essentially an R/q-to-XY conversion.) Significant data collapsing/expanding occurs at short/long ranges.

6. Hardware Architecture

Figure 3 describes a flight simulator and indicates the three interfaces that are important to the DRLMS**:**

- Cockpit/host interface
- Host/DRLMS interface
- DRLMS/cockpit interface

Normally, all radar controls and indicators are interfaced through some sort of linkage to the host computer and the host computer relays this information to the DRLMS on the host/DRLMS interface. The host computer provides, via host/DRLMS interface, simulator data (e.g., initialize, run, freeze), ownship and target position and attitude, and environmental data. The DRLMS generates the radar video and transmits this to the cockpit via the radar/cockpit interface.

Three types of radar video are encountered**:**

- The DRLMS performs scan conversion and creates a raster scan in some standard format such as RS-170.
- High-speed digital serial with encoded range/bearing information to drive a cockpit-mounted scan converter, such as the ARINC-708 standard.
- Analog R/q traces to drive a CRT or scan converter.

Figure 4 is a typical DRLMS hardware block diagram. We routinely build DRLMS using an SGI Challenge workstation configured with four 250MHz R4400 processors and 128Mbytes of RAM. The VMEbus provides the channel for the host interface (shown here as an HSD interface) and the cockpit interface (shown here as a Synergy frame buffer.) This system is usually delivered as a

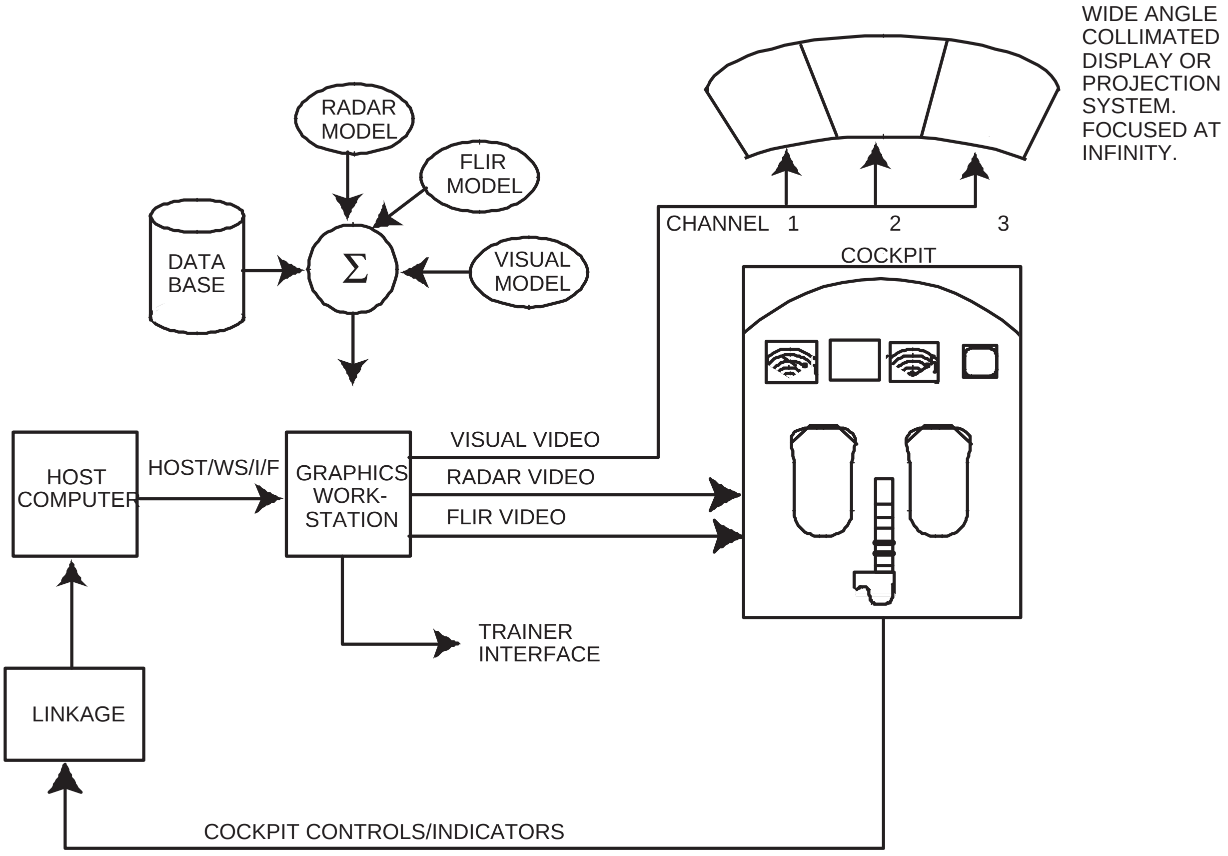

Figure 3. Flight Simulator Functional Block Diagram

rackmounted version and requires no special power or cooling, and has a footprint of less than 4 sq ft. Contrast this with the previous generation of hardware-intensive DRLMS that occupied 8 racks and several hundred square feet, required forced-air cooling, and required special power of 300-500 amps at 5 volts.

7. Software Architecture

The high-level software data flow diagram shown in Figure 5 illustrates the information flow between major software processes. The system runs in realtime and is usually driven by 30Hz interrupts from the host computer.

The system runs the IRIX 5.3 (32-bit) or IRIX 6.2 (64-bit) operating system, both of which are Unix SVR4. We maintain POSIX.4 compliance. All software is written in C++ using Object Oriented Design (OOD) methodologies.

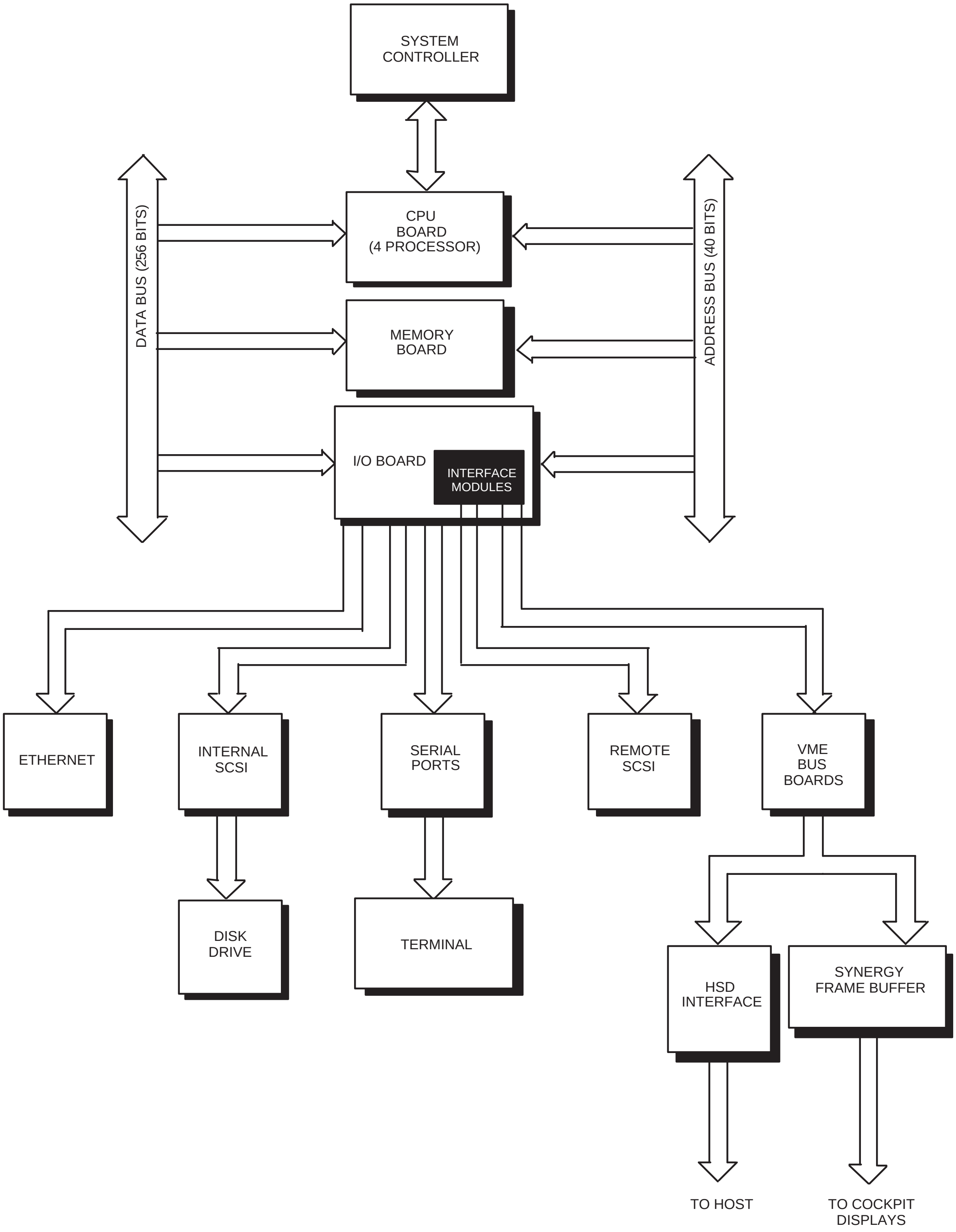

Figure 4. DRLMS Hardware Architecture

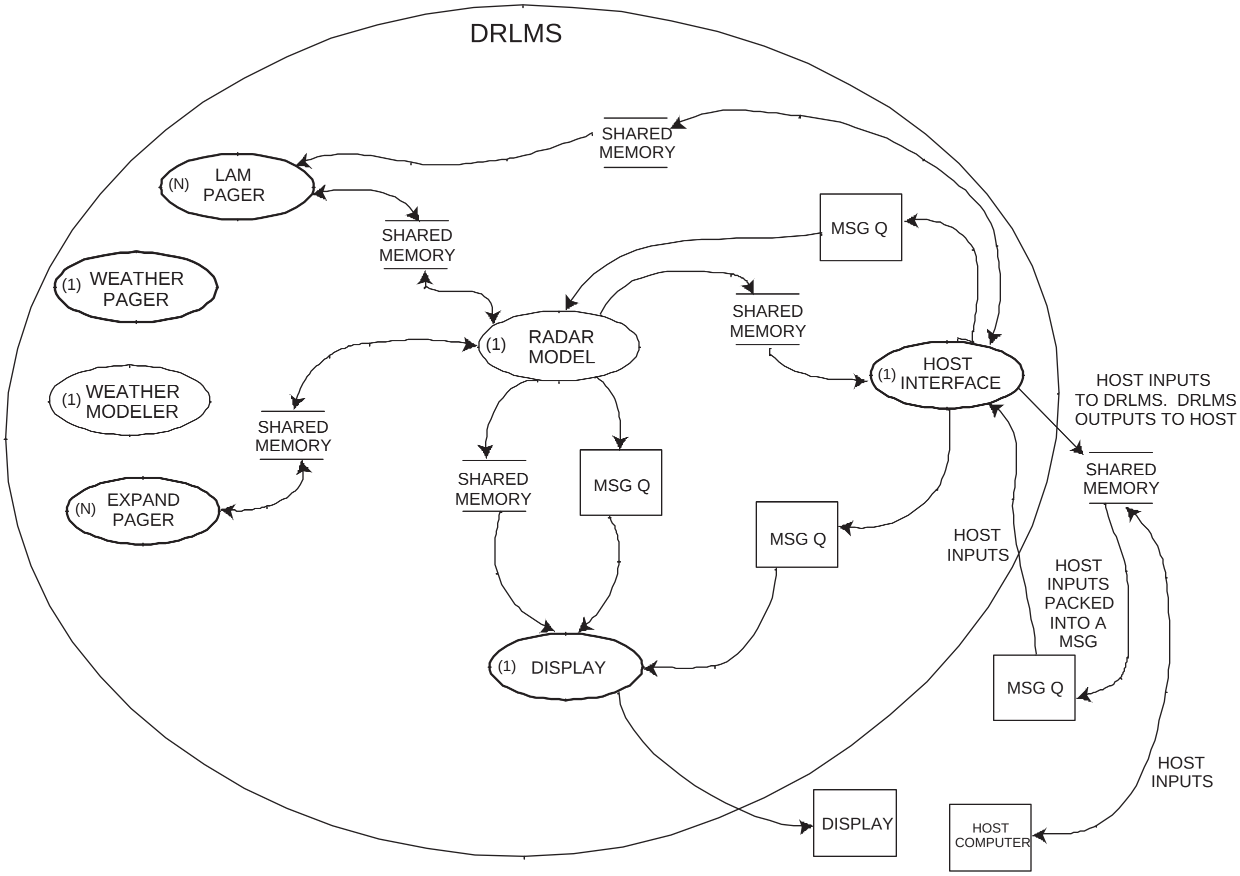

Figure 5. Software Data Flow Diagram

Inter-Processor Communication (IPC) consists of shared memory and message queues. Message queues provide reliable sequencing and reliable data delivery. Shared memory provides an efficient means for passing large volumes of data.

We isolate Unix to a single processor and use system calls for peripherals and interfaces. Tasks are bound to processors and our software contains a variety of methods for prioritization, scheduling and distribution of tasks.

8. Conclusions

Today, the use of commercial workstations and modular software allows for the creation of high-fidelity, realistic Airborne Radar Simulators. These systems are less expensive, easier to modify and more maintainable and reliable than their predecessors.

9. About The Author

George L. Bair received the BS, MS, and PhD degrees in Electrical Engineering from the University Of Missouri–Rolla in 1973, 1974, and 1976, respectively. The emphasis of his degree program was communication systems and signal processing with concurrent studies in mathematics, particularly probability and statistics. While in graduate school, he worked on Office Of Naval Research programs performing analysis and simulation of radar-based navigation systems for missiles and aircraft.

Dr. Bair spent eight years at Texas Instruments, Inc. as a radar systems engineer, and contributed to several advanced development programs for noncoherent, coherent, and continuous wave (CW) radars. He was involved in the design and development of the first coherent millimeter-wave radar with pulse compression. He was involved in the development of the APS-137 radar, the first Inverse Synthetic Aperture Radar (ISAR), for the P-3 aircraft and designed, built, and flight tested the tracking system[3] for the P-3 aircraft.

For the past twelve years he has been building sensor simulators, principally airborne radar simulators at Merit Technology, then at successors SBS Technologies and Camber Corporation. Since his invention in 1985 of a new approach to radar simulation,[4] he has been involved in building 34 radar simulators. Representative systems include A-4, F-5, F-14, F-15, F-16, F-18, P-3, C-130, LANTIRN, and numerous commercial aircraft. This approach—the application of emerging computer technologies and software-only models—has been extended to InfraRed (IR), ElectroOptic (EO), visual, and other sensors to achieve better price/performance/reliability advantages. Dr. Bair currently manages the Dallas Office of Camber Corporation. They design and manufacture RF, IR, and EO sensor simulators, visual image generators, and the environmental models/databases required to support them.

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