



# Future Weather Doppler Radar Feasibility Study

Phase I.

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## 1. Executive Summary

The October 2003 version of the Omnibus Appropriations Bill specifies, “A parallel assessment of the practicality of commercializing the SPY-1 or successor for weather forecasting is funded under the National Weather Service. ... NWS shall submit a feasibility study to the Committees on Appropriations no later than May 1, 2004.” The present document is the result of a two-month, quick-look study effort that addresses these Congressional concerns at a high level. However, a more detailed effort is needed to more quantitatively address cost-benefits and technical details. The results of this report and the language of the Omnibus Appropriations bill are consistent with top-level recommendations found in the “Beyond NEXRAD”<sup>1</sup> report recently prepared by the National Academy of Sciences.

A fundamental NWS issue of concern to Congress is the need to achieve faster, more timely severe weather early warning, at lower cost, and within the framework of the existing NEXRAD Weather Doppler Radar system. Within the context of the Omnibus Appropriations Bill, the AN/SPY-1A is of interest because it is a phased array radar (PAR), capable of tracking multiple objects of interest simultaneously and revisiting these objects much quicker than can the existing NEXRAD Doppler radar. In general, PAR offers fundamental technical advantages that are especially useful for the early detection and tracking of severe storms such as tornados.

Major advances in solid-state radar technology have occurred during the last decade. These advances have been commercialized and implemented in PAR systems. For example, both Ball Aerospace and Lockheed Martin have done extensive research on applying PAR systems to weather applications. CEA Technologies (Canberra, Australia), has developed a commercial PAR system used for air traffic control. Briefings from each of these companies are included in the Appendices of this report.

PAR technology has traditionally been used in high performance military or intelligence systems, but the telecommunications boom of the 1990s changed the economics associated with this technology. Radar techniques formerly envisioned only in unconstrained cost scenarios are now viable for commercial and civil implementation. Even very-low cost applications for automobiles may now be possible. The *New York Times* reported on February 3, 2004 that PAR technology will be used to provide blind spot warning to motorists; tests on crowded freeways near Valeo Raytheon headquarters (Auburn Hills, MI) have already demonstrated the system’s effectiveness.

The current document is limited to identifying the potential of PAR technology for Weather Doppler Radar applications. Numerous science and engineering implications need to be fully understood, and quantified in terms of cost and performance, prior to specifying PAR technology for future weather radar systems.

Our primary conclusions and observations are:

- One company stated that the cost of PAR transmit/receive elements will go from \$1,200 in 1999 to \$250 in 2010; another company informally estimated the 2010 cost at \$100. The Aerospace Corporation thinks that the cost will be closer to \$35, but this estimate needs additional substantiation.
- Market evidence and engineering statistics indicate significant increases to component reliability, which will greatly reduce the impact of single-point-of failure components and result in much lower recurring costs.
- Integration of PAR technology into the existing NEXRAD system could be done gracefully.
- A formal, in-depth analysis is required to provide a clear picture of the costs / benefits of Phased Array Radar for weather Doppler radar application.
- A more comprehensive, top-down study should be undertaken to define architectural requirements and performance objectives that can be addressed by PAR in the 2005-2020 timeframe.
- This comprehensive study needs to be done in concert with the NSSL to quantitatively identify the performance benefits of PAR in terms of severe weather detection and potential savings in life and property.

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<sup>1</sup> New Priorities for the 21<sup>st</sup> Century, Department of Commerce, 31 March 2003.



## 2. Introduction

Future weather forecasting systems will encompass a variety of advanced sensor technologies, including visible, infrared and hyperspectral imagers, as well as new classes of advanced Doppler radars. Such active and passive sensors are expected to provide greatly enhanced detection times for severe storms and to provide increasingly accurate weather forecasts.

It is likely that these technologies will be implemented on a variety of ground, oceanic, airborne and space platforms. This document focuses on PAR implemented on ground based fixed and mobile platforms. The following issues will require further investigation:

- Is it likely that low-cost commercial PAR will be available in 2012?
- What is the likely cost of a PAR system in that timeframe?
- How does this cost compare with that of the NEXRAD system?
- How do the key performance parameters of a PAR system compare with those of NEXRAD?
- Is a PAR system a likely replacement for NEXRAD, or should PAR technology be viewed as a supplement to an enhanced NEXRAD system?

Figure 2-1 illustrates a notional view of the weather radar systems architecture. The operations control centers that process and analyze weather data are not shown in Figure 2-1, because they have been excluded from the scope of this study. Today's weather forecasting system includes all platforms shown in Figure 2-1, except the UAV and PAR platforms.

Current weather forecasting systems have excellent capabilities for predicting, detecting and tracking hurricanes and storms. Accurately predicting severe storms and hurricanes can provide early warning for affected areas in hope of minimizing loss of life and property. Scientific and technological advances in image sensors, radars, signal and data processing algorithms, computers, networks, and system integration are likely to greatly enhance current capabilities in weather forecasting, storm detection and storm track prediction.

According to NOAA, in year 2000 there were 14 tornados in the US, resulting in loss of 40 lives and millions of dollars in property damage. In 2002 there were 28 tornados, resulting in loss of 55 lives and millions of dollars in property damage. In 2003 there were 18 tornados, resulting in 51 deaths and millions dollars in property damage. PAR is a technology that may be well suited for the early detection of developing tornados. Enhanced early warning should result in saving lives, and may help mitigate property damage.

To improve the performance of current radar systems, NOAA and NSSL technical team members are in the process of evaluating PAR technology. Until recently, PAR technology was practical only for military radars because of the high cost. However, the commercial wireless telecommunications boom in the late 1990s enabled high volume production of antenna elements, RF components, digital signal processing components and signal processing algorithms. As a result, many component costs have been decreased by an order of magnitude. Since high cost was the primary obstacle blocking development of commercial PARs, and given the extremely high performance of PAR, it is reasonable to expect extensive commercialization of PAR in the near future.

The Aerospace Corporation has been tasked to assess and evaluate Phased Array Antennas (PAA) and Transmitter / Receiver Modules (TRM) for NOAA in terms of their commercial viability. The objective is to examine the potential for minimizing life cycle costs, deployment schedules, technical performance improvements, while providing backwards interoperability to existing control and operations centers. Conceptually, this represents the front end of a phased array radar, as depicted in Figure 2-2.

Technological and manufacturing advancements in the areas of solid state amplifiers, switches, analog to digital converters, and low noise amplifiers are enabling the replacement of phased array antenna panels that use passive components (*i.e.*, wave guides, coax cables, phase shifters) with panels that use active radar components. As will be seen, there are substantial advantages associated with PAR. In Appendix D, Lockheed Martin Corporation

(Camden, NJ) indicates that the cost of PAR TRM elements has dropped from \$2,000 in 1995 to \$1,200 in 1999. This cost is expected to decline substantially over the next decade.

The lower cost of TRM elements is being driven by the commercial wireless telecommunications industry and by technology advancements in the electronics components industry. Companies such as CEA Technologies PTY Limited (Canberra, Australia) have already produced relatively inexpensive commercial, active phased array systems. However, new technologies and their development always raise questions regarding risk. Throughout this quick-look study, we provide some examples and rationales regarding risk mitigation approaches.

The basic structure of this report deserves comment, since the brevity of the study and the complexity of its subject, have demanded an abbreviated approach.

Section 3 discusses current PAR and provides a review of capabilities, performance advantages and costs. These parameters can be used to establish a preliminary reference model. Section 4 discusses weather physics issues that form the fundamental basis for all Doppler weather radar systems. Section 5 describes a tentative architecture for a future phased array Doppler weather radar. This section provides some calculations of power versus number of TRM elements, and a discussion of interfaces and functional requirements. It also provides an engineering basis for future PAR feasibility studies. Many “To Be Determined” items appear in the latter section; these will be resolved in a more detailed study. Section 6 provides recommendations of the future weather radar. Subsequent sections contain acronyms, appendices and references.

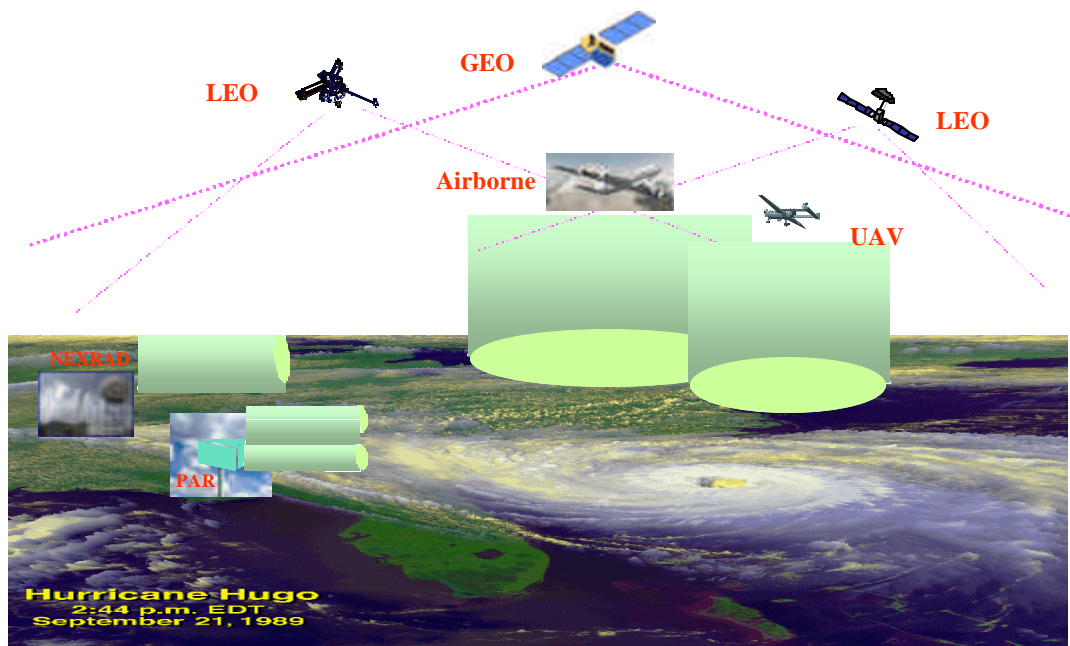


Figure 2-1. Notional View of Weather Radar Systems Architecture



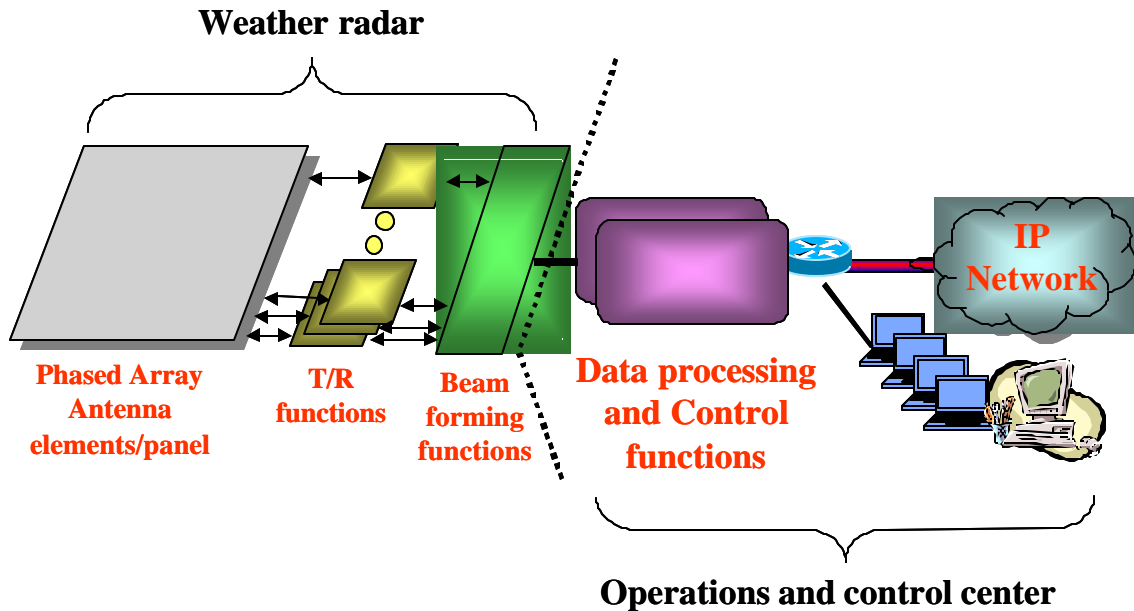


Figure 2-2. High Level Functional Boundaries of Ground Based Weather Radar

### 3. Review of Current Phased Array Radar

This section reviews today's PAR technology, performance and cost as used in military and commercial applications. Because of its traditionally specialized applications (and resulting high costs), phased array radar has been historically limited to military applications. However, recent technology advancements, process improvements, and mass production of key components enabled by the wireless telecommunications industry suggest that a new look at the commercialization<sup>2</sup> of phased array radar is in order.

Comments regarding *passive* versus *active* PAR are necessary. Passive PAR has been developed since mid-1970s; it was deployed in the early 1980s for military applications in airborne, ship-borne, and ground-based platforms. Because of its superior performance in detecting and tracking multiple targets simultaneously, its high development costs were justified for meeting military requirements. Classical examples of military passive PAR systems can be found in the JSTARS (Air Force airborne surveillance radar), the AN/SPY-1x (Navy ship-borne Aegis combat system radar), and the Patriot (Army mobile ground-based anti-missile radar).

Much newer active PAR, with beam forming technology, represents the latest version of the PAR for the commercial market. It is the construction of the phased array antenna that most distinguishes active PAR from passive PAR. Passive PAR includes an antenna panel with phased array TRM elements (either in dipole or patch configurations); also included are analog phase shifters, klystron, RF "plumbing" with wave-guides and coaxial cables.

Figure 3-1 shows a high-level functional diagram for a passive PAR. Typical examples of passive military PAR can be found in the Patriot (which includes about 5000 elements and phase shifters per panel), and the AN/SPY-1x (which includes about 4000 elements and phase shifters per panel).

<sup>2</sup> For this study, the definition of commercialization includes design of a PAR with commercially available components and a sufficient manufacturing volume to sufficiently lower the production cost.

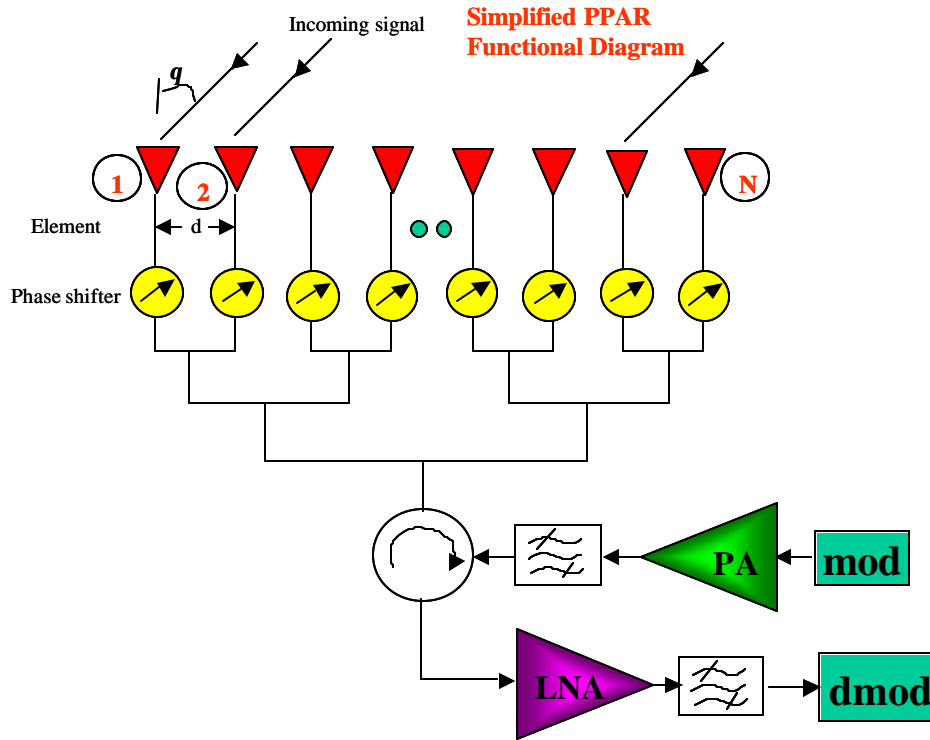


Figure 3-1. Passive PAR Functional Diagram

Passive PAR, as seen in Figure 3-1, includes an antenna module and TRMs; such systems are based on highly integrated mechanical and analog components. High power transmit amplifiers and low noise receive amplifiers are required. For simplicity, other major components (*e.g.*, local oscillators, up-converters, down-converters, *etc.*) in the TRMs are not shown in the above figure. Because of its analog design characteristics, passive PAR has inherent limitations in agility, as well as longer settling times. It is based on the beam steering technology. Furthermore, this presents severe limitations in availability and scalability. To achieve higher system availability, passive PAR requires redundant transmitters and receivers.

The two most commonly evaluated performance parameters in passive PAR systems are: effective isotropic radiated power (EIRP) and antenna gain-to-system-noise-temperature ration (G/T). Assuming a planar array configuration with a matched square lattice (*i.e.*,  $D=p$ ,  $d=0.5p$ ), the EIRP and G/T for a passive PAR can be expressed as follows:

$$EIRP = NaPD(1 - b^2)$$

where

$N$  = number of elements

$a$  = loss efficiency

$b$  = reflection coefficient

$$D \text{ (directivity of one element)} = \frac{4p}{l^2} (d_x d_y) \cos q$$

$P$  = power amplifier output

and :

$$G = NDa(1 - b^2)$$

$$T = T_a + (F - 1)T_0$$

where

$$T_a = aT_A + T_0(1 - a)$$

$T_A$  = antenna temperature

$T_0$  = ambient temperature (290<sup>0</sup> K)

$F$  = noise figure

Note that the factor  $\alpha$ , which lies between 0 and 1, simply estimates the overall system efficiency (a theoretically perfect system would have  $\alpha = 1$ ).

Active PAR leads to some substantial advantages. Figure 3-2 illustrates a high level functional diagram for an active PAR. An obvious advantage of active PAR is its inherent agility and scalability, features that are lacking in passive PAR. Active PAR eliminates the mechanical RF “plumbing” and uses distributed, low-power solid state power amplifiers (SSPAs), instead of a centralized high-power transmit amplifier based on a klystron or traveling wave tube amplifier (TWTA).

Because of the distributed nature of SSPAs and low noise amplifiers (LNAs) in active PAR, failures are gradual and graceful. This means that maintenance can be scheduled in advance. With aid from built-in test circuits, performance degradations and maintenance of SSPAs and LNAs are predictable. Significantly, active PAR eliminates single point of failure in the RF front-end modules. This means that there is no need for redundancy and no need to stock spare parts at the 100% level. In addition, active PAR does not require a special cooling system because its power amplifiers are based on multiple low-power SSPAs (rather than a single high-power cooled klystron, as used in passive PAR). Thus, ambient cooling can be used in active PAR, which significantly reduces life cycle costs for the system.

In active PAR, antenna elements are closely coupled with the TRMs. These are then tightly integrated with the digital beam forming circuits and modulator/demodulators. Depending upon the geometry and the number of simultaneous transmit and receive beams, the beam forming modules can be distributed in various forms. For example, it could include multiple independent beam forming circuits as shown in Figure 3-2. If the radar system requires complex beams with multiple configurations, the beam forming circuits can be expanded accordingly.

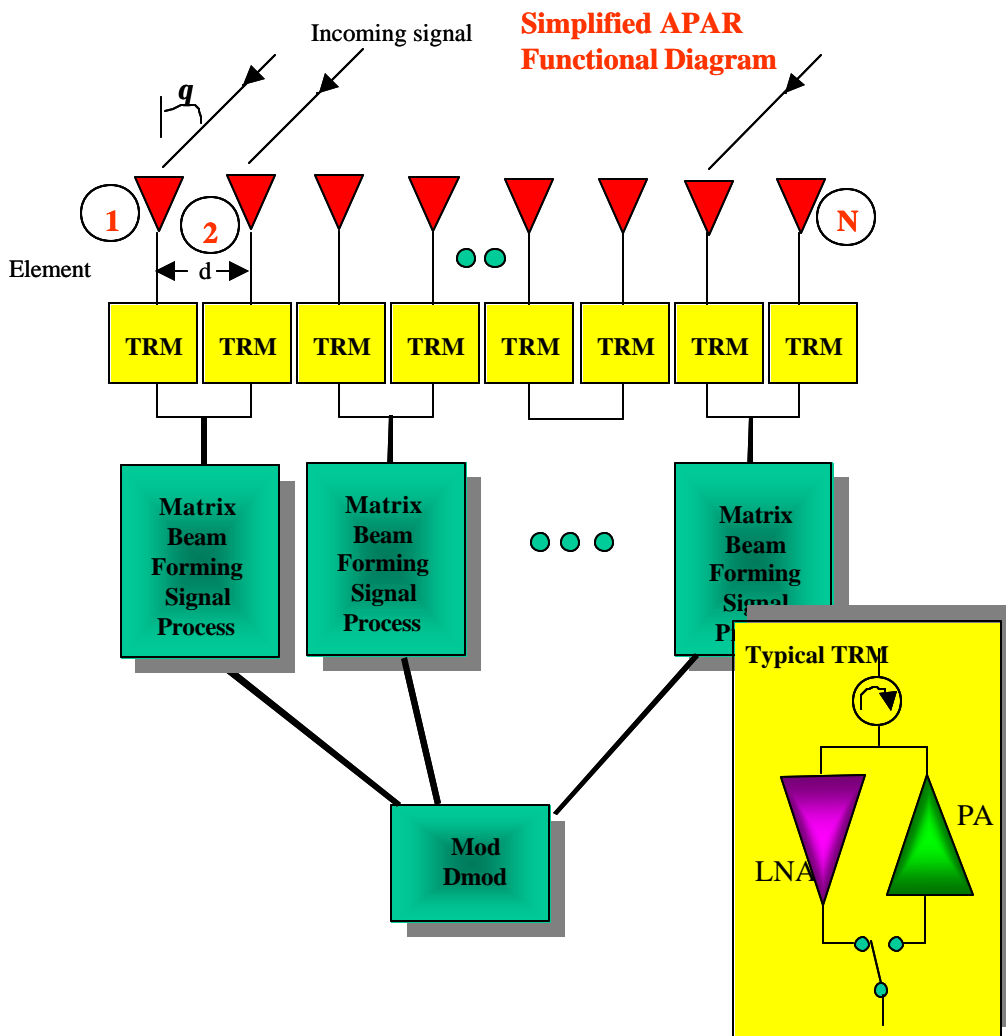


Figure 3-2. Active PAR Functional Diagram



For simplicity, other major components (*e.g.*, the local oscillators, up-converters, down-converters, *etc.*) in the TRM are not shown in Figure 3-2.

As in passive PAR, EIRP and G/T are the two most commonly evaluated performance parameters. Assuming a planar array configuration with matched square lattice (*i.e.*,  $D=p$ ,  $d=0.5p$ ), the EIRP and G/T for passive PAR can be expressed as follows:

$$EIRP = N^2 a P D (1 - b^2)$$

where

$N$  = number of elements

$a$  = loss efficiency

$b$  = reflection coefficient

$$D \text{ (directivity of one element)} = \frac{4P}{I^2} (d_x d_y) \cos \theta$$

$P$  = power amplifier output

---


$$G = ND(1 - b^2)$$

$$T = T_a + (F - 1)T_0$$

where

$$T_a = T_A$$

$T_A$  = antenna temperature

$T_0$  = ambient temperature (290<sup>0</sup> K)

### 3.1 Survey of Military and Commercial Phased Array Radar

As noted in the previous section, there are two categories of PAR, active and passive. Early military PAR systems were based on passive technology. More recently, there have been several commercial and civil satellite programs (*e.g.*, Iridium<sup>3</sup> and TRMM<sup>4</sup>) that have used active phased array antenna technology.

Perhaps the Navy's AN/SPY-1A<sup>5</sup> and the Army's Patriot are the most widely deployed passive PAR military systems. A brief summary of the AN/SPY-1A physical appearance and technical characteristics is given in Appendix F. Recently, a modified AN/SPY-1A was installed at the NSSL (Norman, OK), where it is being used to assess PAR for weather applications.

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<sup>3</sup> Iridium is a commercial communications satellite, operating in low earth orbit. It includes 3 active phased array antenna panels.

<sup>4</sup> TRMM (Tropical Rainfall Measuring Mission) is a joint project between the US and Japan. It is a low earth orbit satellite with an active phased array radar operating at 13.8 GHz.

<sup>5</sup> A modified AN/SPY-1A radar was recently installed at the NSSL (Norman, OK), where it is being evaluated. It was modified for weather applications by Lockheed Martin (Camden, NJ).



Table 3-2 includes key functional parameters of the modified version of the AN/SPY-1A.

**Table 3-1. AN/SPY-1A Passive PAR Functional Parameters**

System Functions	
Parameters	Specifications
<b>Active/Passive PAR</b>	<b>Passive</b>
Transmit functions	See Figure 3.1
Receive functions	See Figure 3.1
Signal Processing functions	Block diagrams (TBD)
Digital Beam Forming method	Beam steering
Beamwidth (deg) & beam patterns	1.5 (bore sight), 2.1 (slant +/- 45) TBD
Waveform	Pulsed short (1.57 μs) and long (4.71 μs)
Freq-Diversity Pol-Diversity	N/A (designed for single frequency and single polarization)
Number of beams (Tx)	TBD
Number of beams (Rx)	TBD
Remote operations, test, diagnostic, and maintenance	interface diagrams (TBD)
Local operations, test, diagnostic, and maintenance	interface diagrams (TBD)
Scaleability	N/A (designed for fixed platform)
Portability	N/A (designed for fixed platform)

Table 3-2 includes key performance parameters of the modified version of the AN/SPY-1A.

**Table 3-2. AN/SPY-1A Passive PAR Performance Parameters**

System Performance	
Parameters (unit)	Specifications
Tx=Rx Freq (GHz)	3.195
Bandwidth (kHz)	TBD
Coverage Range (km)	460
Detection Range (km)	460
Pulse Repetition Freq (kHz)	TBD
EIRP (dBW)	TBD
G/T (dB-K)	TBD
Elevation coverage (deg)	0.5 to 55 (14 steps for volume scan takes less than 60s)
Range resolution (m)	230
Angle accuracy (deg)	TBD
Settling time (ms)	TBD
Clutter suppression (dB)	TBD
Side lobe suppression (dB)	TBD
Rx sensitivity (dBm)	TBD
RF Dynamic Range (dB)	TBD
ADC Dynamic Range (dB)	TBD
Prob of detection	TBD



System Performance	
Parameters (unit)	Specifications
Prob of false alarm	TBD
Availability (reliability)	TBD

Table 3-3 includes key design parameters of the phased array antennas of the modified version of the AN/SPY-1A.

**Table 3-3. AN/SPY-1A Passive PAR Performance Parameters**

Antenna Performance Parameters	
Parameters (unit)	Specifications
Tx=Rx Freq (GHz)	3.195
Antenna Tx Gain (dBi)	TBD
Antenna Rx Gain (dBi)	TBD
Polarization	Linear vertical
G/T (dB-K)	TBD
Front to back ratio (dB)	TBD

Table 3-4 includes key physical parameters of the phased array antennas of the modified version of the AN/SPY-1A.

**Table 3-4. AN/SPY-1A Passive PAR Physical Parameters**

Antenna Physical Parameters	
Parameters (unit)	Specifications
Number of elements/panel	4352 (68 modules, 32 elements/module)
Number of Tx and Rx modules	1 Tx and 1 Rx
Number of A/D and DSP	TBD
Panel size, volume & geometry	~40' x 40', ~hexagonal-like flat panel
Panel weight (kg)	TBD
Power consumption (W)	TBD
Cooling method	Chilled water, forced convection
Altitude/Op-Temp/Op-Humidity	TBD
Wind loading/Vib/Shock	TBD
Lightening protection	TBD
Connectors	TBD
Mounting structures	TBD

### 3.2 AN/SPY-1A PAR Test Results from the NSSL

An AN/SPY-1A PAR was recently installed at the NSSL. This radar is currently being tested and evaluated for weather applications.

Table 3-5 includes NEXRAD Doppler radar specifications. To verify the AN/SPY-1A performance, it is necessary to compare its specifications with those for NEXRAD where applicable and possible. Of course, the NEXRAD and the AN/SPY-1A are different systems that were designed for different purposes. The AN/SPY-1A was designed to detect and track multiple small hard targets moving with high velocity. The present intent is not to make a line-by-line specification comparison, but to assess the general capabilities of the AN/SPY-1A for weather applications. A logical approach is to compare the key parameters of the AN/SPY-1A with those of NEXRAD that may measure



PAR suitability for future weather applications. For example, multiple beams for tracking multiple weather targets and conditions (e.g., large amorphous targets with both slow and fast velocities), range resolutions, pointing accuracies, settling time, etc.

Table 3-5. Performance Comparisons<sup>6</sup>

Parameters	Values (SPY-1A)	Values (NEXRAD)
Detection Range		
Reflectivity (km)	460 km	460 (~248 NM)
Velocity (km)	460 km	230 (~124 NM)
Angular Coverage		
Azimuth (deg)	360 or a fixed sector	Full circle or sector
Elevation (deg)	0.5 to 55	-1 to +20
<b>Antenna</b>		
Type	Passive Phased Array, S-band, 4352 elements and phase shifters	S-band, center fed, parabolic dish
Reflector aperture	NA	8.54 m (28 ft) diameter, circular
3 dB Beamwidth, one-way (deg)	1.5 (bore-sight) 2.1 (± 45 deg)	0.96 @ 2.7 GHz 0.88 @ 3.0 GHz
Gain		45.8 dBi @ 2.85 GHz (mid-band)
Polarization	Linear, Vertical	Linear, Horizontal
1 <sup>st</sup> side lobe level		-29 dB
Steerability (deg)		360 az, -1 to +45 el
Mechanical limits (deg)	NA	-1 to +60
El Rotational rate (deg/s)	NA	30
Az rotational rate (deg/s)	NA	36
Angular acceleration (deg/s <sup>2</sup> )	NA	15
Pointing accuracy (deg)	NA	± 0.2
<b>Radome</b>		
Type	Fiberglass skin, form sandwich	Fiberglass skin, form sandwich
Diameter	TBD	11.89 m (39 ft)
RF loss, two-way (dB)	TBD	0.3 ± 0.06 dB over 2.7 to 3.0 GHz
<b>Transmitter</b>		
Type	Master Osc power amp	Master Osc power amp
Frequency (GHz)	3.195	2.7 to 3.0
Peak power output (kW)	600	750
Average power output (kW)		1.56
Pulse width nominal (us)	1.57 (short pulse) 4.5 (long pulse), ± 4%	1.57 (short pulse) 4.5 (long pulse), ± 4%
RF duty cycle (max)	800 μs	0.002
Range sample (m)	15	250
Number of simultaneous Tx beams	1	NA

<sup>6</sup> Data shown in Table 3.5 are obtained from the NSSL in January 2004.



## NOAA Future Weather Doppler Radar Study



Parameters	Values (SPY-1A)	Values (NEXRAD)
<b>Pulse repetition frequency</b>		
Long pulse (Hz)	TBD	322 to 422 ( ± 1.7%)
Short pulse (Hz)	TBD	322 to 1282 ( ± 1.7%)
Waveform	TBD	Contiguous and batch
<b>Receiver</b>		
Type	Linear	Linear
Frequency (GHz)	3.195	2.7 to 3.0
3 dB bandwidth (MHz)	TBD	0.63 (short pulse) 0.22 (long pulse)
Phase control	TBD	Selectable
Rx channels output	Linear I/Q	Linear I/Q, log
Dynamic range (dB)	TBD	95 max, 93 @ 1 dB compression
Rx sensitivity (dBm)	TBD	-113
Noise temp (deg K)	TBD	450
IF (MHz)	TBD	57.6
Sampling rate (kHz)	10000, 5000, 2500	600
Number of simultaneous Rx beams	1	NA
<b>Signal Processor</b>		
Type	SKY, 5 boards , each with 4 power PCs	Hardwired/programmable
Derived parameters	Reflectivity, mean radial velocity, Doppler spectral width	Reflectivity, mean radial velocity, Doppler spectral width
Algorithms	16 & 32 pulse FFT, pulse-pair	Power averaging, pulse-pair, single-lag, correlation
<b>Accuracy</b>		
Reflectivity (dB)	TBD	< 1
Velocity and spectrum width (m/s)	TBD	< 1
<b>Number of pulses averaged</b>		
Reflectivity	Selectable	6 to 64
Velocity and spectrum width	Selectable	40 to 200
<b>Range resolution</b>		
Reflectivity (km)	0.23	1
Velocity and spectrum width (km)	0.23	0.25
<b>Azimuth resolution</b>		
Reflectivity (deg)	Variable	1
Velocity and spectrum width (deg)	Variable	1
Clutter suppression (dB)	TBD	30 to 50
Notch filter half width (m/s)	TBD	0.5 to 4
Loss efficiency	TBD	
Directivity of one element	TBD	



### 3.3 AN/SPY-1A PAR Lessons Learned from the NSSL Test Bed

NSSL testing of an AN/SPY-1A PAR is currently underway. It is anticipated that more extensive data comparisons with NEXRAD data will occur in the near future.

From the weather radar systems engineering perspective, it is good to have a higher G/T; however, a higher EIRP is not needed, because long-range detection of incoming missiles is obviously not a weather service issue. Desirable weather PAR attributes are listed below in random order of importance:

- High-agile clutter rejection ratio and high side-band suppression ratio.
- High dynamic range with adequate receiver sensitivity.
- No moving parts, heavy-duty RF plumbing or cooling.
- No components that are prone to be single-point-failures.
- Multiple transmit-receive beams (simultaneous) with independent beam forming capabilities.
- On-the-fly beam width control for each beam (varying degrees from narrow to wide).
- Fast beam scanning and settling time capabilities, with higher range and angle resolutions.
- On-the-fly frequency, waveform, and polarization diversities.
- Control the sampling rate and do I/Q sampling at IF rather than at base band.
- Real time signature processing algorithms that will perform statistical correlation between models and detected weather phenomena (e.g., wind velocity, moisture density, pressure and temperature).
- Networked radar stations allowing data from different stations to be simultaneously analyzed at central or regional control centers.
- Micro-radar platforms (small scale radar sites) sandwiched between macro radar platforms (large scale radar sites, similar to the current NEXRAD sites) to optimize data collection granularity.
- Mobile radar platforms to support quick deployment at changing, high-need areas.

### 3.4 CEA-FAR

The CEA-FAR was originally designed for the Australian Navy. CEA technologies later converted this product for commercial markets. It includes modularized panels, TRMs and DSPs, which allow scaleable integration of the radar. Table 3-6 includes key performance parameters. It is based on an active PAR that requires no wave-guide and includes GaAs MMIC phase shifters with large scale FPGA and high speed DSPs (1600 MIPS). Appendix C includes a technical overview of the CEA-FAR.

**Table 3-6. Key Performance of CEA-FAR**

Parameters (unit)	Area Surveillance System	Full Capability System
Tx/Rx frequency	L, S, or X band	L, S, or X band
Bandwidth (MHz)	> 400	> 400
Panel height (m)	1.35	2.7
Panel width (m)	2.7	3.4
Antenna weight per panel (kg)	<400	<800
# of elements per panel	64	64
Signal processing modules	2	6
Detection range (km)	40 against small missile targets (waveform and scan dependent)	70 against small missile targets (waveform and scan dependent)
Clutter rejection (dB)	45 to 65 (waveform dependent)	45 to 65 (waveform dependent)

## NOAA Future Weather Doppler Radar Study



Elevation coverage (deg)	± 60	± 60
Angle accuracy (deg)	Az = 0.7	Az = 0.5
Track while scan	El = 1.3	El = 0.7
Angle accuracy (deg)	Az < 0.4	Az < 0.2
Track mode	El < 0.6	El < 0.3
Revisit time (s)	<1	<1
Horizontal search mode		
Revisit time (s)	<0.3	<0.3
Height interest tracks		
Typical range (NM)	108	216
Antenna side lobes (dBc)	-25 to -35	-25 to -35
Cooling	Natural	Natural
Modulator Agility and Waveform	Pulse to pulse or burst to burst Simultaneous multi-freq	Pulse to pulse or burst to burst Simultaneous multi-freq
Sampling rate (MSPS)	160	160
A/D resolution (bits)	14	14
Parallel processing DSP (MIPS)	25,600	25,600
Power supply (kW)	5	



### 3.5 Summary of Current Phased Array Radar

This quick-look study has examined both military and commercial versions of phased array radar. Some performance comparisons between the AN/SPY-1A and NEXRAD are also provided. It is too early to make total system performance comparisons (due to the limited test data from the NSSL). However, it is reasonable to state that active PAR with adaptive beam forming algorithms, frequency diversity, polarization diversity and waveform diversity will provide significant improvements in predicting severe weather conditions. These advantages should be especially important for tornado prediction. Section 5 will consider how active PAR technology might be implemented for future weather Doppler radar applications.

## 4. Weather Physics

### 4.1 Weather and Radar

This section is intended to provide a succinct discussion of the fundamental physical principles that underlie practical weather radar. Its purpose is to show in general terms why radar systems designed for weather monitoring assume the technical characteristics that embody today's systems, and whether such characteristics lend themselves to future advances that may provide greater performance and lower costs.

One may ask why radar is so useful for probing the state of the atmosphere. When examined in the most fundamental terms, radar consists of the generation and manipulation of photons whose frequencies interact very weakly with gas-phase atmospheric molecules, but reflect strongly from airborne macroscopic constituents. Stated differently, radio frequencies are not appreciably absorbed by aerosols, major gases of the atmosphere (78%  $N_2$  and 21%  $O_2$ ) or the remaining 1% of various trace gases (mostly  $H_2O$  and  $CO_2$ ). Molecular transitions that absorb photons commonly occur in the high frequency spectral region, where photon wavelengths are in the  $1 \times 10^{-6}$  m range. Photons of much lower energy (wavelengths in the 0.01 to 0.3 m range) do not strongly interact with molecular electronic states, and hence are chosen for probing atmospheric properties.

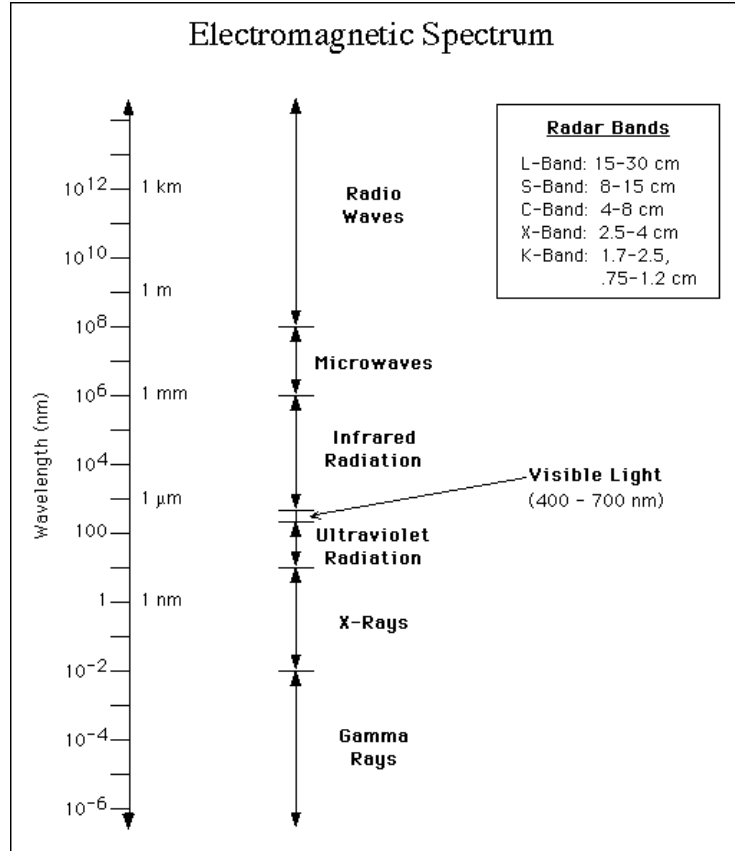


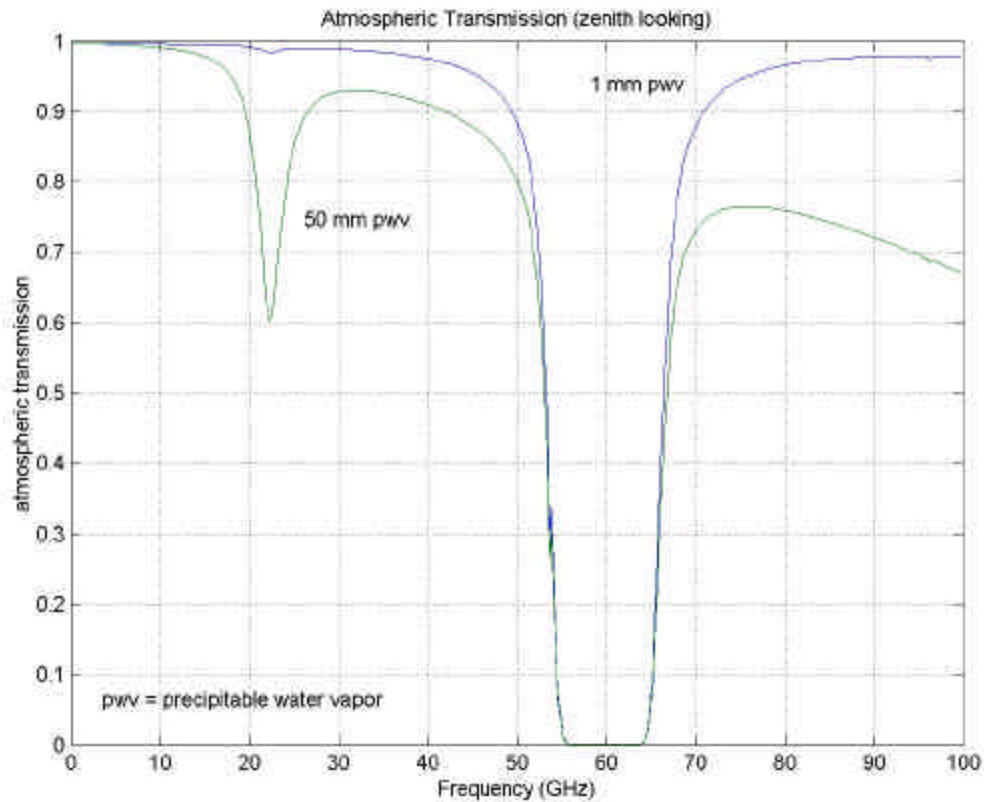
Figure 4-1. The Electromagnetic Spectrum

The IEEE has developed the following designations for the radiofrequency portion of the electromagnetic spectrum. These are shown in Table 4-1.

Table 4-1. IEEE RF Band Designations

Band	Frequency (GHz)	Wavelength (cm)
L	1 - 2	30 - 15
S	2 - 4	15 - 7.5
C	4 - 8	7.5 - 3.75
X	8 - 12	3.75 - 2.50
Ku	12 - 18	2.5 - 1.67
K	18 - 27	1.67 - 1.11
Ka	27 - 40	1.11 - 0.75
V	40 - 75	
W	75 - 110	
mm	110 - 300	
u mm	300 - 3000	

The great virtue of the radiofrequency portion of the electromagnetic spectrum is its ability to penetrate the atmosphere. Figure 4-1 shows the transmission of the atmosphere as a function of frequency in the 0.5 to 100 GHz range; the absorption features are due mostly to gaseous  $H_2O$  and  $O_2$ . Even in the presence of substantial precipitable water vapor, the atmosphere has essentially unity transparency in the 0.5 to 30 GHz range, even with the presence of water vapor, and hence the suitability of radars in that range for meteorological purposes.



**Figure 4-2. Atmospheric Transmission vs. Frequency**

The relative advantages of S, C or S bands for weather radar depend strongly on the range and attenuation requirements for particular weather applications. The precise choice of frequency will depend of the scattering cross sections for the objects of interest. For example, the drop size and shape distributions of ice, snow, rain or hail will vary. These weather phenomena impress differing signatures on a reflected RF pulse, since the physical characteristics of a reflecting object vary according its size, shape, or scattering cross section.

Several kinds of basic radar techniques are in common use, including continuous wave (CW), pulsed, pulsed Doppler and synthetic aperture. CW radar operates by transmitting RF energy in a continuous stream. Objects that intersect this beam will reflect portions of the transmitted energy back toward a receiver; this sort of radar gives an indication of the presence of an object, but not its range. Pulsed radar breaks the RF transmission into discrete pulses, whose duration and duty cycle are known. If the time delay between the transmission of a given pulse and its travel time after reflection from an object is measured, the range to the object can be computed. Doing this for many pulses improves the signal-to-noise ratio for the range calculation. Pulsed Doppler radar is similar to pulsed radar, except the slight frequency shift that the Doppler effect causes is also measures, which provides the velocity of the object with respect to the receiver in addition to the range. When several spatially separated pulsed Doppler radars are used together, two-dimensional maps of object velocities can be measured. Synthetic aperture radar uses a combination of the pulse time-delay measurement to obtain a range sample; and the relative motion of the radar with respect to objects of interest to create a synthetic baseline from which azimuth information can be derived. The



combination of range and azimuth data are then synthesized mathematically to produce a two dimensional image of a scene.

There are numerous variants on the basic radar techniques just mentioned. However, this study is concerned with PAR, and how it compares with pulsed Doppler radar,<sup>1,2</sup> which is the technique used by NEXRAD (and most other weather radars).

Pulsed Doppler radar in the S band regime is of value because of its ability to map out reflectivity and velocity within regions that are enshrouded by storm clouds. However, producing a three-dimensional representation of a storm requires about 2 to 5 minutes of time, with the time limit basically defined by the need to physically move the radar antenna and the need to transmit and receive enough radar pulses to achieve an adequate signal-to-noise ratio. Severe weather phenomena obviously can change very rapidly during a 2 to 5 minute interval, which illustrates the need to achieve rapid spatial pointing and high data rates. Of course, the intrinsic inertia associated with mechanical Doppler radar antennas is completely eliminated by electronic steering, and is a major potential advance for weather radar sensing.

The physical means by which a radar transmitter directs a series of pulses toward a target, and by which the receiver detects very weak energy from reflected pulses, greatly influences how effectively a given radar sensing technique can be implemented. For example, the need to physically move the transmit/receive antenna imposes fundamental limitations on the speed with which data can be collected. Mechanical structures associated with weather radars must usually be both rugged and heavy, since they must survive stressful environments and also not be prohibitively expensive. Although electronic switching and computing may occur on time scales in the nanosecond ( $10^{-9}$ ) range, the movement and reaction of massive antennas occurs in timeframes greater than 1 millisecond ( $> 10^{-3}$  s). It can be seen that important performance limiting factors for weather radars are linked to fundamental characteristics of the currently implemented pulsed Doppler radar technology, namely mechanically-steered systems.

Phased array radar systems avoid some fundamental limitations and performance bottlenecks of mechanically steered radars. This is done by mounting many small transmit / receive elements on flat or curved surfaces. A computer then controls the firing of specific transmitters and the reception of return signals by specific receivers. Control of the phase relationship (i.e., the slight time variation between the operation of groups of transmitter elements and groups of receiver elements) permits extraordinarily rapid operation of the antenna. The shape and direction of the transmit beams can be rapidly altered, and the array antenna can be adaptively operated to null out interference from RF noise sources or intentional jamming. These characteristics are of obvious importance for military and intelligence systems. The more recent use of array antennas for commercial systems reflects the changing markets and costs for phased array technology.

As is true of any sensor system, the characteristics of the sensor must be designed to measure the physical observables that directly or indirectly provide information that is useful in a “real world” context. For example, a Doppler radar system is capable of measuring small differences between the frequency of a transmitted RF pulse and the frequency of the reflected pulse. These frequency shifts are used to derive quantities that describe the state of the atmosphere. In the case of Doppler radar, the frequency difference and its sign provide a measure of wind velocity and wind direction. The energy of the reflected pulses can be used to compute the spatial extent of precipitation, and observing the variation of reflected pulse energy as a function of frequency can provide a measure of the kind of precipitation that is present.

Suppose a radar transmitter emits a pulse of frequency  $f_0$  (corresponding to a wavelength  $\lambda$ ), and suppose the pulse travels outward, is reflected from some object (such as rain or hail) at a range  $r$  from the radar, propagates back toward the radar and is collected by a receiver. The total traversed distance  $2r$  measured in terms of wavelength is  $2r/\lambda$  or,  $2\pi(2r/\lambda) = 4\pi r/\lambda$  radians. If the transmitted wave has an initial phase of  $\phi_0$  then the phase after it returns will be

$$\phi = \phi_0 + 4\pi r/\lambda$$

The change of phase as a function of time is then

$$d\phi/dt = (4\pi/\lambda) dr/dt$$



where  $dr/dt$  is the target radial velocity  $v$  and the quantity  $d\phi/dt$  is the target angular frequency  $2\pi f_d$ . Substitution gives,

$$f_d = 2v/\lambda$$

where  $f_d$  is Doppler shift frequency of the target. At the center of the S band (3 GHz), an object heading radially toward (or away) from a radar at 40 mph (about 18 m/s) would have a Doppler shift of only about 180 Hz. A pulsed Doppler radar corresponds discrete time and space sampling of the target medium, where time corresponds to the pulse repetition time (PRT) and space to the sample volume depth of the radar. Thus the maximum unambiguous,  $r_{max}$ , the maximum range to which a transmitted pulse wave can travel and return to the radar before the next pulse is transmitted, is:

$$r_{max} = c \text{ PRT}/2 \text{ or } r_{max} = c / 2(1/\text{PRF})$$

where  $c$  is the speed of light and PRF is the pulse repetition frequency of the transmitted pulse train. Sampling at the radar PRT interval also limits the maximum frequency that can be resolved. The rigor for this is given by the Nyquist Sampling Theorem, which simply states that the sampling rate PRF must be at least twice the rate of the maximum unambiguous Doppler frequency  $f_{max}$ , i.e.,

$$f_{max} = \text{PRF}/2$$

that corresponds to a maximum Doppler velocity of

$$v_{max} = (\text{PRF}) \lambda/4 .$$

Combining the maximum range and velocity gives

$$r_{max} v_{max} = c\lambda/8$$

This shows that one has to compromise between  $r_{max}$  and  $v_{max}$  for a given radar. There are, however, some advanced techniques such as staggered PRT, phase coding, *etc.*, that allows for an increased  $v_{max}$  without compromising  $r_{max}$  up to a certain limit.

A pulsed Doppler radar emits a train of intense microwave pulses that leave the antenna in essentially a collimated beam. In the absence of attenuation, the incident power density  $S_i$  on a target at range  $r$  and direction  $\theta, \phi$  is given by

$$S_i(r, \theta, \phi) = P_t g_t f^2(\theta, \phi) / (4\pi r^2)$$

Where  $f^2(\theta, \phi)$  is the normalized power gain (defined as unity along the beam axis),  $g_t$  is the antenna gain, and  $P_t$  is the power delivered to the antenna's waveguide port.

Transmitted pulses are reflected and backscattered by atmospheric phenomena of interest (snow, hail, water drops, *etc.*) or clutter (birds, airplanes, *etc.*). The scattering cross section  $\sigma_b$  is an apparent area that intercepts a power  $\sigma_b S_i$  which, if radiates isotropically, produces at the receiver a power density

$$S_r = \sigma_b S_i / (4\pi r^2)$$

equal to that scattered by the actual hydrometeor. Mie theory<sup>3</sup> provides a general solution for the scattering of a plane wave by a sphere. At non-attenuating wavelengths, *i.e.* for scatterers with radii much smaller than the radar wavelength, a more involved Mie solution can be approximated by:

$$\sigma_i = (\pi^5/\lambda^4) |K|^2 D_i^6$$





known as Rayleigh approximation.  $\sigma_i$  is backscattering cross section of individual scatterers with diameter  $D_i$  and  $K = (m^2 - 1)/(m^2 + 2)$  where  $m$  is the complex index of refraction. Knowing  $\sigma_i$ , the total backscattered power received at the antenna for Rayleigh scattering is <sup>1</sup>:

$$\overline{P_r} = \frac{C|K|^2 Z}{r^2}$$

where  $C$  is a radar constant and  $Z$  is radar reflectivity factor that can be calculated from:

$$Z = \int_0^{\infty} D^6 N(D) dD$$

where  $N(D)$  is drop size distribution and  $N(D)dD$  gives the number of particles per unit volume with diameters between  $D$  and  $D+dD$ . For a wide range of rain and snow one can write  $N(D)$  as a two parameter drop size distribution as:

$$N(D) = N_0 e^{-\Lambda D}$$

In the same way that  $Z$  can be related to drop size distribution, other parameters of interest such as precipitation rate,  $R$ , and liquid water content,  $W$ , are also related to drop size distribution. Therefore, under certain conditions a unique relationship between  $Z$  and  $R$  can generally expressed as:

$$Z = aR^b$$

There is a fundamental trade-off between area coverage for velocity (requires more spatial separation) and greater spatial resolution (requires greater sensor density). It is important to note that microbursts and divergent flows require spatial resolutions in 100 m range. This has been a special area of concern for air traffic, since most hazardous shears for flight are within few 100 m of surface. If small-scale diverging flows are to be detected, only high angular resolution ( $\leq 1$  deg) radars will suffice. Wind shear has very short time scale (microbursts in the 5-15 minute range, with severe wind shear in the 2-4 minute range and average velocity difference of only 25 m/s across the divergent flow. It is significant that small-scale (but highly dangerous) phenomena are sometimes buried in larger-scale (and longer lived) mesocyclones, gust fronts, *etc.*

Microburst prediction is an extremely significant requirement for modern severe weather warning systems. Practical experience has identified several microburst indicators that can be observed with Doppler radar.<sup>4</sup> These are:

- A descending high reflectivity core.
- A mid-level velocity convergence within and near the cloud base.
- A reflectivity notch and rotation
- Divergent winds near the surface.

The first two indicators occur before the advent of microburst winds; the presence of a reflectivity notch and rotation are good predictors only if the first two phenomena are observed; the fourth effect occurs during the microburst event.



## 4.2 Improving Tornado Detections and Warnings with Weather Radars

A tornado is a violently rotating column of air extending from a thunderstorm to the ground. These destructive forces of nature are found most frequently in the United States east of the Rocky Mountains during the spring and summer months. In an average year, 800 tornadoes are reported nationwide, resulting in 80 deaths and over 1,500 injuries. Based on their shapes and sizes tornadoes are grouped into three categories:

1. Weak Tornadoes (F0-F1 on the Fujita scale) with winds less than 110 mph and lifetime of 1-10+ minutes constitute about 69% of all tornadoes and responsible for less than 5% of tornado annual deaths.
2. Strong Tornadoes (F2-F3) with 110-205 mph winds that may last 20 minutes or longer. These tornadoes constitute about 29% of all tornadoes and causes nearly 30% of tornado annual deaths.
3. Violent Tornadoes (F4-F5) with greater than 205 mph winds that can last for more than 1 hour. Only 2% of all tornadoes fall into this category but they cause about 70% of all tornado deaths in the country.

Figure 4-2 shows the total number of tornadoes and the corresponding number of deaths between the years 1961 and 1993. To accurately establish the risk posed by tornadoes, it is important to know the frequency and location of tornado occurrences. Figure 4-3 depicts geographical distribution of tornado related statistics across the country.

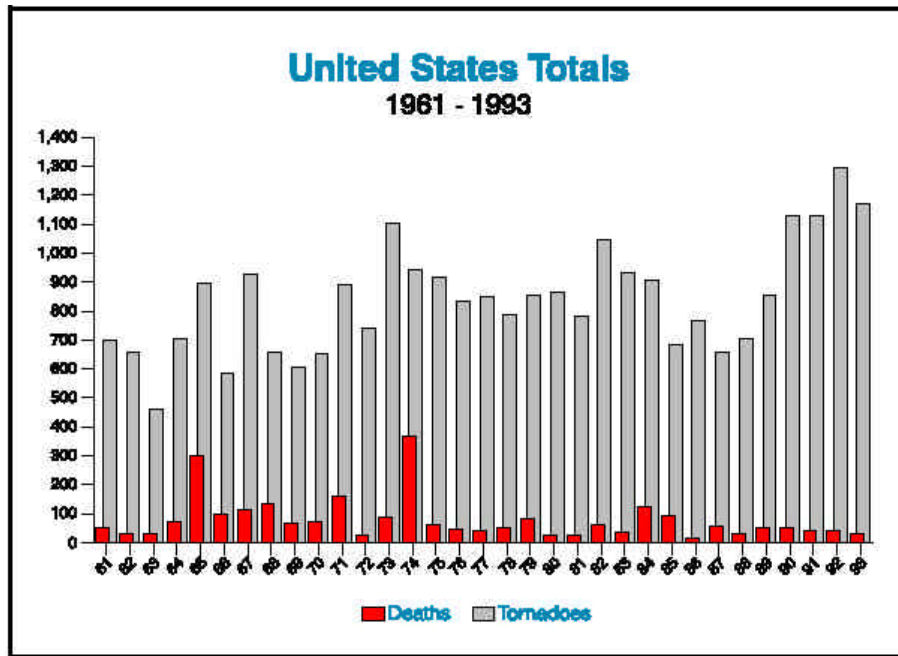


Figure 4-2. Tornado Statistics<sup>5</sup>

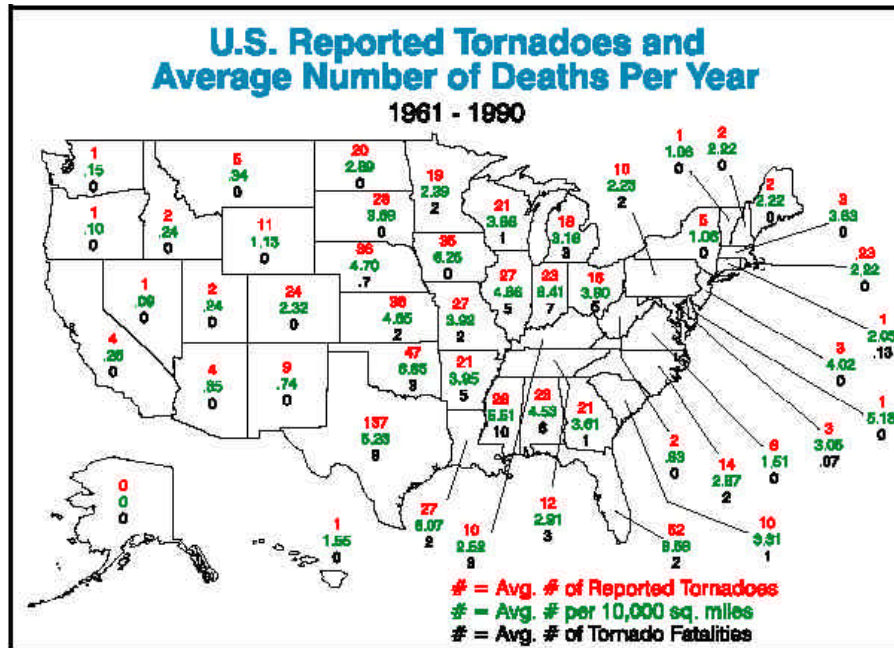


Figure 4-3. Geographical Tornado Distribution

### 4.3 Improved Tornado Detection Using Weather Radars and the Prospect for Improvement

When a Doppler radar scans a tornado, depending on the size of the radar half-power beam width relative to the size of the tornado, it can generate either a tornado signature (TS) or a tornadic vortex signature (TVS) on radar displays. If the tornado's core diameter is larger than radar's effective half-power beam width a tornado signature occurs. In contrast, a tornado vortex signature occurs when the tornado's core diameter is smaller than radar's effective half-power beam width.<sup>6</sup> In both cases, the signature is identified by extreme Doppler velocity values of opposite signs on opposing sides of the signature. Forecasters monitor Doppler radar displays, looking for indications that tornado formation within a storm is imminent.

Tornado probability of detection and its associated warning lead-time have substantially improved since late 1980s, and the WSR-88D radar network is a major contributor for this improvement. Figure 4-4 shows that tornado warning lead times have continuously improved since 1992. This improvement, however, diminishes as the distance between the radar and tornado increases. At far distances, a radar beam typically passes over the tornado well above the ground, owing to the curvature of the earth. This phenomenon is illustrated in Figure 4-5. A high-density radar network, with each radar covering not more than a few tens of kilometers, can mitigate this problem. Another problem that limits current radar capabilities is the relatively long time intervals between volume scans, currently around 5-10 minutes; during this time, significant evolution in low-level vortex structure may occur. Proposed phased array Doppler weather radar can substantially reduce this long volume scan time. With these and other improvements, a substantial lead-time improvement, as currently sought by the NWS over the next decade (see Figure 4-4), can be achieved in the near future.

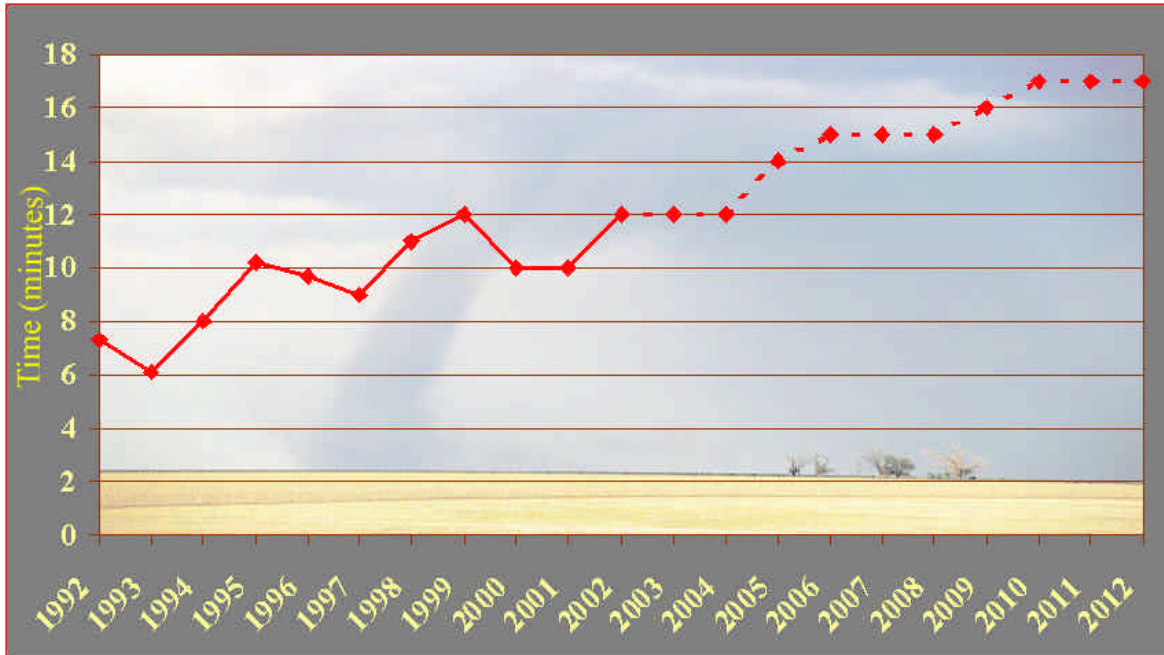


Figure 4-4. Tornado Lead Times<sup>7</sup>

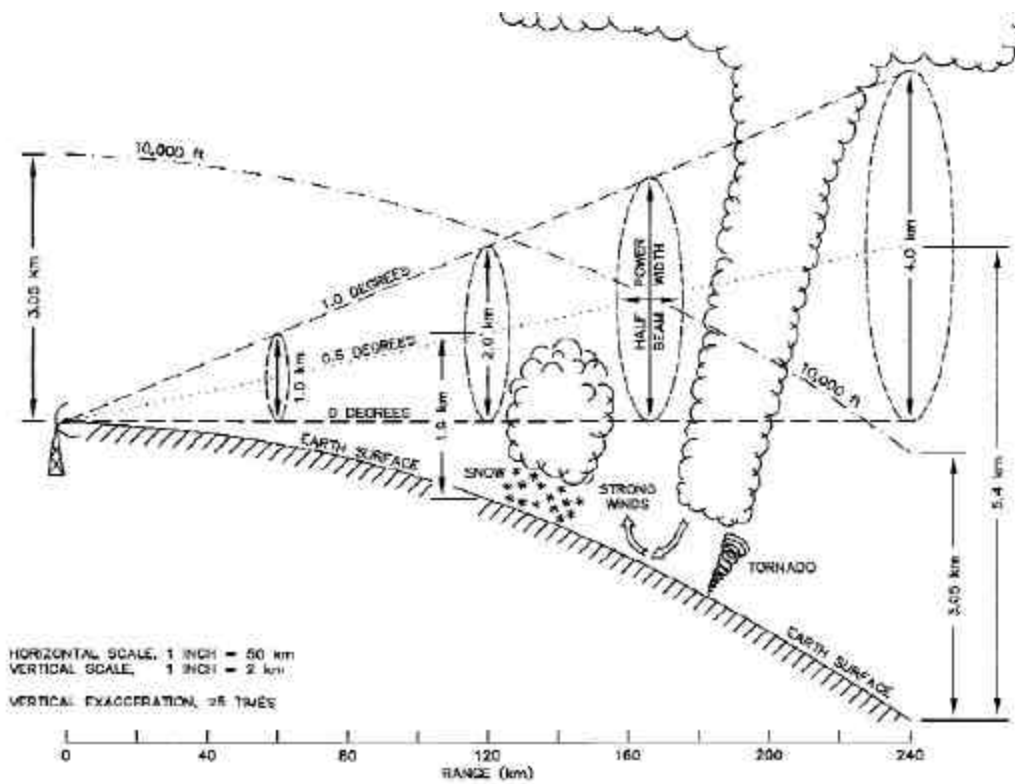


Figure 4-5. Tornadoes and the Earth's Curvature<sup>8</sup>



## 5. Future Weather Radar

### 5.1 Active PAR Parameter Calculations

As discussed above, the scope of this quick-look effort has been limited to a feasibility study of the RF front-end infrastructure for future radar systems. Some of the items omitted from this effort are algorithm development of signal/image processing and modeling efforts. These will be critical for the real time analysis and correlation that will tie observables to weather phenomena.

There are three fundamental parameter values that will dominate the upper bound of performance and cost issues. They are:

- Transmit-Receive Frequency
- EIRP
- G/T

The FCC and military spectrum allocations in most radar systems include the L, S, C and X-bands.<sup>7</sup> The L-band and C-band spectra are very crowded today. Most terrestrial wireless telecommunications systems and GPS systems use the L-band spectrum, and most commercial satellite communications systems use the C-band spectrum. S-band is frequently used by satellite systems for telemetry and commanding. This leaves a choice between S-band and X-band. Securing frequency allocation is a significant task that needs to be performed before the specifications of a future active phased array Doppler weather system are defined.

S-band is the frequency range of choice because it is not susceptible to rain attenuation,<sup>8</sup> and requires inexpensive components to design transmit/receive modules.

Budgeting adequate EIRP is critical in radar systems because it determines the detection range capability and the RF subsystem cost. The current NEXRAD EIRP is 102.78 dBW (klystron running at peak power, and the frequency at mid S-band), which provides a reflectivity detection range up to 460 km. Assuming the peak to average ratio of 7 dB, the average EIRP is 95.78 dBW.

Computing the detection range for an S-band PAR is useful for understanding how system requirements must be defined for a future system. The following calculations provide some estimates:

The path loss in free space is defined as:

$$L_{fs} = 92.45 + 20 \log(f) + 20 \log(d)$$

$f$  = frequency in GHz

$d$  = distance in km

This equation says that, holding the frequency as a constant variable, the path loss in free space is 20 dB per decade of range. Starting with an EIRP value of 6 dB below the average EIRP of NEXRAD will reduce coverage range by one-half; the starting EIRP is then 89.78 dBW. This may not provide a sufficient coverage, but will provide a rough estimate for sizing the antenna panel and the required number of elements per panel. Using this EIRP, the number of elements required for the active and passive phased array can be simulated, which in turn provides a rough cost estimate that can be tied back to detection range requirements.

Figure 5-1 shows the simulation results that will produce about 90 dBW of EIRP using an active phased array antenna (assuming  $F = 3$  GHz, and  $P = 10$ W per amplifier). Note that the factor  $\alpha$ , which lies between 0 and 1, simply estimates the overall system efficiency (a theoretically perfect system would have  $\alpha = 1$ ).

<sup>7</sup> See Figure 4-1 and Table 4-1 for definitions of these bands.

<sup>8</sup> See Figure 4-2.



$$EIRP = N^2 a P D (1 - b^2)$$

where

$N$  = number of elements

$a$  = loss efficiency

$b$  = reflection coefficient

$$D \text{ (directivity of one element)} = \frac{4P}{I^2} (d_x d_y) \cos q$$

$P$  = power amplifier output

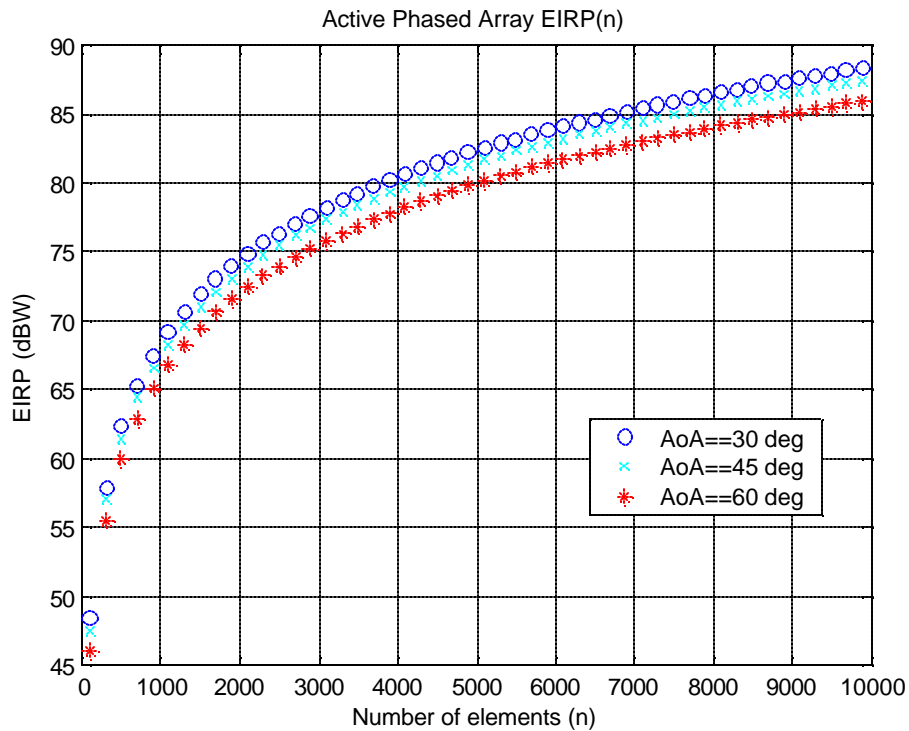


Figure 5-1. Active Phased Array EIRP vs. Elements

Using a 10 W amplifier for each element, it appears that the active phased array antenna will require about 10,000 elements to produce EIRP of 90 dBW.

It would require about 100 kW amplifier for the passive phased array antenna to produce a similar EIRP; the simulation result is shown in Figure 5-2.

$$EIRP = NaPD(1 - b^2)$$

where

$N$  = number of elements

$a$  = loss efficiency

$b$  = reflection coefficient

$$D \text{ (directivity of one element)} = \frac{4P}{I^2} (d_x d_y) \cos q$$

$P$  = power amplifier output

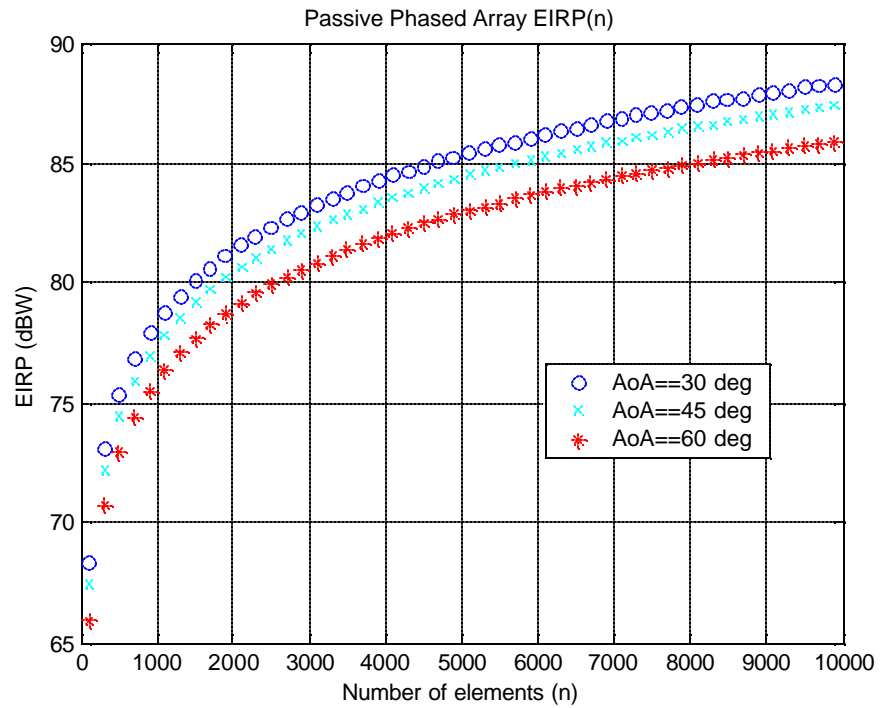


Figure 5-2. Passive Phased Array EIRP vs. Elements



Holding the number of elements used in EIRP simulations constant, simulated G/T for an active phased array antenna can be computed;<sup>9</sup> the simulation result is shown in Figure 5-3.

$$G = ND(1 - b^2)$$

$$T = T_a + (F - 1)T_0$$

where

$$T_a = T_A$$

$T_A$  = antenna temperature

$T_0$  = ambient temperature (290<sup>0</sup> K)

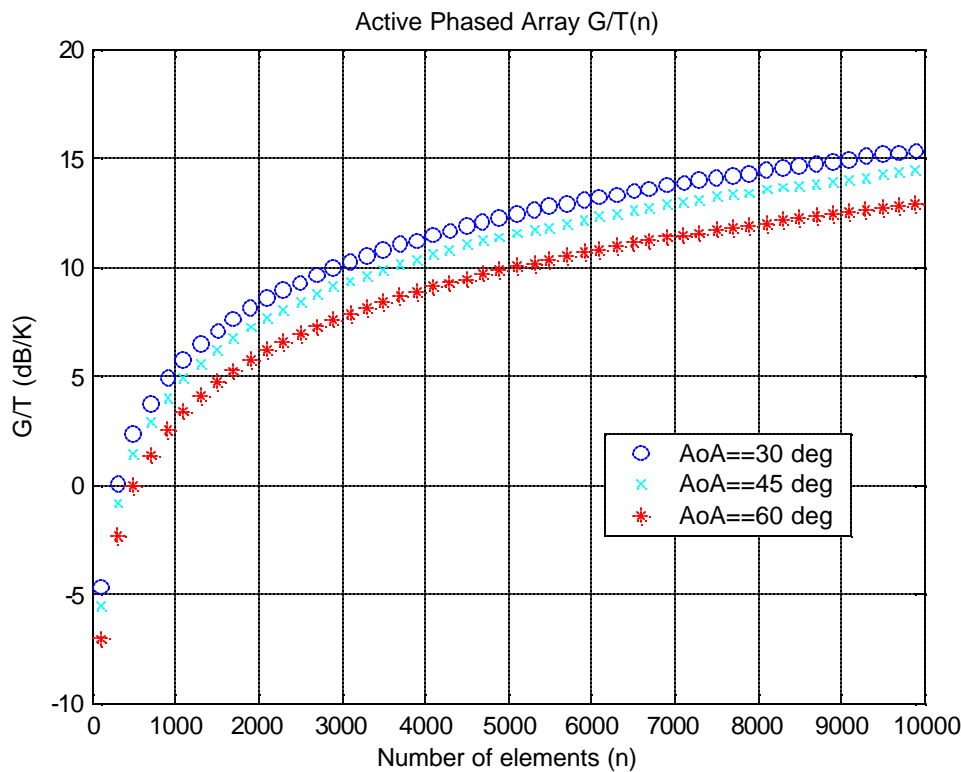


Figure 5-3. Active Phased Array G/T vs. Elements

A similar simulation was conducted for a passive phased array antenna,<sup>9</sup> and the result is shown in Figure 5-4.

<sup>9</sup> Assumed antenna temperature of 300 K.





$$G = NDa(1 - b^2)$$

$$T = T_a + (F - 1)T_0$$

where

$$T_a = aT_A + T_0(1 - a)$$

$T_A$  = antenna temperature

$T_0$  = ambient temperature (290<sup>0</sup> K)

$F$  = noise figure

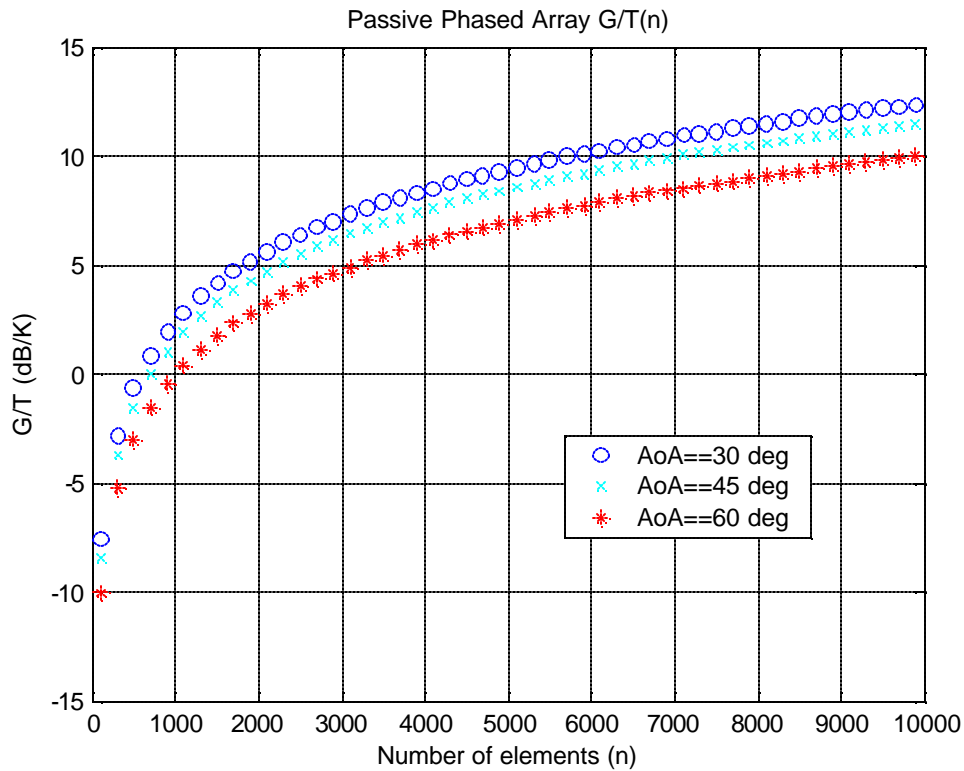
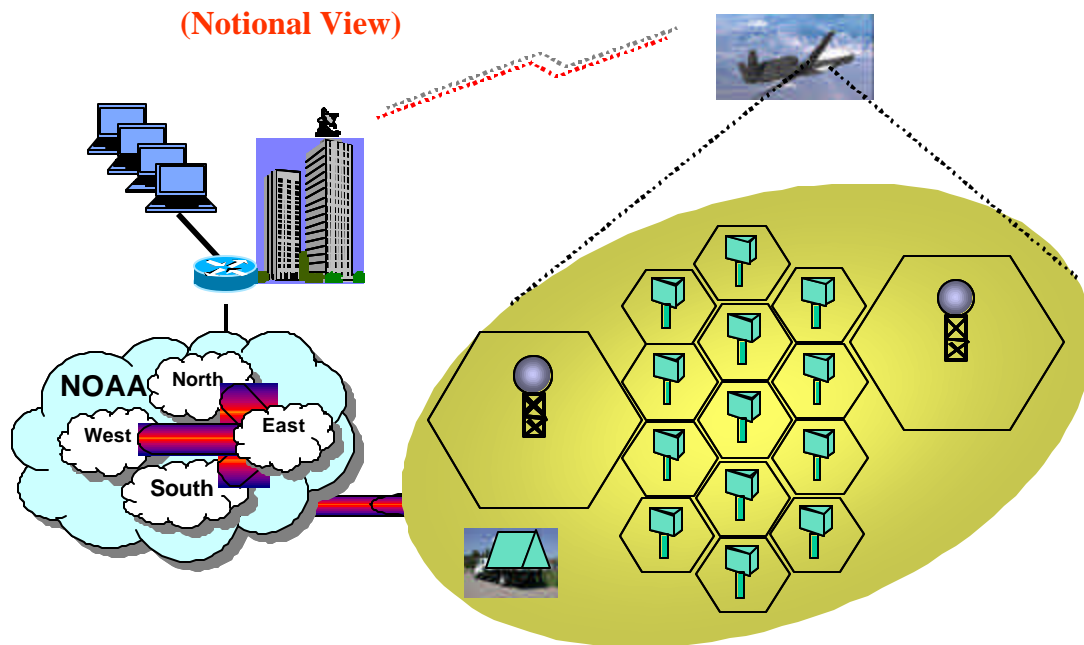


Figure 5-4. Passive Phased Array G/T vs. Elements

With a rough estimate of the required number of elements as a starting point, optimum values for the EIRP can be assessed to meet weather Doppler radar requirements.

## 5.2 Ground Based Weather Doppler Radar Systems Architecture

Figure 5-5 illustrates a notional view for a ground based weather Doppler radar system. Although this section will focus on fixed, ground-based weather Doppler radars, it is envisioned that UAV radar platforms may play a role in future weather radar system operations.



**Figure 5-5. Notional View of a Ground-Based Weather Doppler Radar System**

A ground based fixed platform size and performance suite may vary, depending upon the locations and surrounding environment. Figure 5-5 illustrates small radar sites (micro sites) sandwiched between the large sites (macro sites). Each site could be connected to an IP network (either private or public) with adequate security to form a wide area network between the sites and regional and central operations-control centers. The observed weather data from each site could be transferred over the network and made available from the regional and central operations-control centers for real time processing.

Some macro sites may include 3 or 4 panels to cover 360 degrees azimuth, and some micro sites may include 2 or 3 panels to cover sectorized areas that depend upon the location and environment. In addition, each panel may be configured with varying number of element. This architecture will provide flexibility for configuring each site based on current coverage needs, and thus enable reduced life-cycle costs.

### 5.2.1 Functional Allocations

Figure 5-6 illustrates the high level functional allocations of a weather radar systems front-end which includes the antenna, RF, interface (IF), and Base Band (BB) modules.

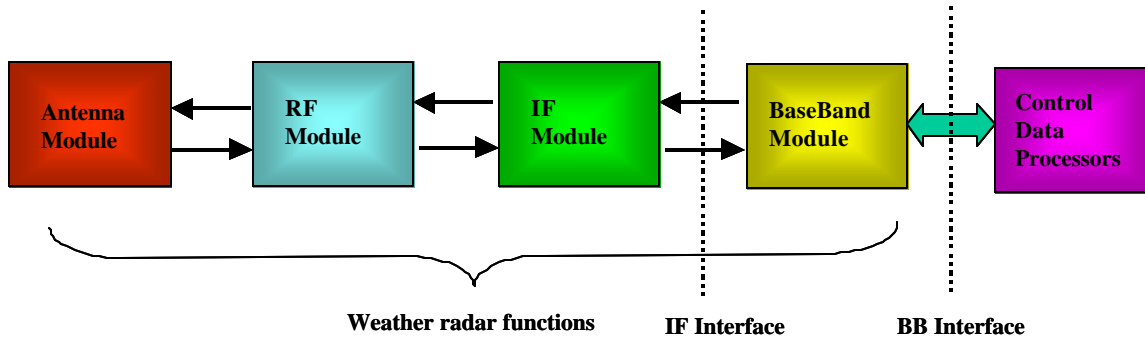


Figure 5-6. Functional Allocations of a Weather Radar

The antenna module will consist of the elements, phase shifters, and panels. The number of panels per site and number of elements per panel may vary depending on the coverage objectives and the geographical location of the sites. The RFM<sup>10</sup> will consist of the filters, circulators, transmit power amplifiers, low noise amplifiers, and switches. The IFM will consist of the filters, down converters, up converters and local oscillators. To eliminate RF plumbing, the IF and RF modules will be integrated in the antenna panels. The BB modules will consist of the analog to digital converters, digital to analog converters, ASICs and DSPs to modulate and demodulate signals. The BB modules will be integrated in a separate frame.

### 5.2.2 Interface Definitions

There are two external interface boundaries in the future weather radar, as shown in Figure 5-6. The IF interface boundary provides in-phase and quadrature (I/Q) serial analog signals between the BB modules and IF modules. The BB interface boundary provides parallel digital data between the BB module and control and data processors. The systems will include clearly defined open interfaces between the IF modules and base band modules; between the base band modules and control-data processors; and between control-data processing modules and operations-control centers. The interfaces between control-data processing modules and operations-control centers could be either in private or public IP network, assuming adequate security.

### 5.3 Requirements

The weather radar requirements will cover both system level requirements and design level requirements. The system level requirements will include functional requirements, performance requirements, interface requirements, environmental requirements, and physical requirements as a fixed station platform; the design requirements will focus on the active phased array antenna.

<sup>10</sup> The TRM will include both RFM and IFM.



Weather Doppler radar system requirements are partitioned in 5 categories, and antenna design requirements are partitioned in 2 categories:

- Functional requirements (system)
- Performance requirements (system & antenna design)
- Interface requirements (system)
- Environmental requirements (system)
- Physical requirements (system & antenna design)

In the following sections, the required parameters are defined. Nearly all of their values are TBD through a future effort.

### 5.3.1 Functional Requirements

Key functional requirements for a future weather radar system are listed in Table 5-1.

**Table 5-1. Key Functional Requirements**

System Functional Requirements		
RQ ID #	Parameters	Specification (TBD)
FRQ-001	Transmit	TBD
FRQ-002	Receive	TBD
FRQ-003	Frequency Diversity	TBD
FRQ-004	Polarization Diversity	TBD
FRQ-005	Waveform Diversity	TBD
FRQ-006	ADC sampling diversity	TBD
FRQ-007	Scalability	TBD
FRQ-008	Remote operation, test, maintenance	TBD
FRQ-009	Local operation, test, maintenance	TBD
FRQ-010	Digital beam forming/steering	TBD
FRQ-011	Digital signal/data processing	TBD
FRQ-012	Built in Test, modular level	TBD
FRQ-013	Hot insertion and removal of modules/boards	TBD
FRQ-014	Real-time signal and data processing	TBD
FRQ-015	Real-time operating system	TBD
FRQ-015	Emergency Power	TBD

### 5.3.2 Performance Requirements

Key performance requirements for a future weather radar system are listed in Table 5-2.

**Table 5-2. Key Performance Requirements**

System Performance Requirements		
RQ ID #	Parameters (units)	Specification (TBD)
PRQ-001	Tx/Rx Frequency	S-band / X-band
PRQ-002	EIRP (dBm)	TBD
PRQ-003	G/T (dB-K)	TBD
PRQ-004	Front-to-back ratio (dB)	TBD
PRQ-005	Reflectivity detection range (km)	TBD



System Performance Requirements		
RQ ID #	Parameters (units)	Specification (TBD)
PRQ-006	Pulse repetition frequency (kHz)	TBD
PRQ-007	Elevation coverage/steps (deg)	TBD
PRQ-008	Range resolution (m)	TBD
PRQ-009	Angle accuracy (deg)	TBD
PRQ-010	Settling time (ms)	TBD
PRQ-011	Clutter suppression (dB)	TBD
PRQ-012	Side lobe suppression (dB)	TBD
PRQ-013	Receiver sensitivity (dBm)	TBD
PRQ-014	RF dynamic range (dB)	TBD
PRQ-015	ADC resolution (bits)	TBD
PRQ-016	Probability of detection	TBD
PRQ-017	Probability of false alarm	TBD
PRQ-018	Lead time (min)	TBD
PRQ-019	Availability <sup>11</sup>	TBD
PRQ-020	Carrier Freq stability	TBD
PRQ-021	Phase noise	TBD
PRQ-022	MIPS	TBD
PRQ-023	Memory	TBD
PRQ-024	Throughput	TBD

### 5.3.3 Interface Requirements

Key interface requirements for a future weather radar system are listed in Table 5-3.

Table 5-3. Key Interface Requirements

System Interface Requirements		
RQ ID #	Parameters	Specification (TBD)
IRQ-001	Power interface (normal/emergency)	AC/DC/UPS
IRQ-002	Control interface	TBD Protocols and format
IRQ-003	Data interface	TBD Protocols and format
IRQ-004	Type of connectors & cables	TBD
IRQ-005	Local Operation, Maintenance and Test interface	TBD Protocols and format
IRQ-006	Remote Operation, Maintenance and Test interface	TBD Protocols and format
IRQ-007	IF in-phase	
IRQ-008	IF quadrature phase	

<sup>11</sup> Availability is defined as  $MTBF/(MTBF+MTTR)$ , where MTBF is mean time between failures and MTTR is mean time to repair.

### 5.3.4 Environmental Requirements

Key environmental requirements for a future weather radar system are listed in Table 5-4

**Table 5-4. Key Environmental Requirements**

System Environmental Requirements		
RQ ID #	Parameters (unit)	Specification (TBD)
ERQ-001	Operating temp (deg C)	TBD
ERQ-002	Humidity (%)	TBD
ERQ-003	Shock (g)	TBD
ERQ-004	3 axis Vibration	TBD
ERQ-005	Cooling method	TBD
ERQ-006	Altitude	TBD
ERQ-007	Wind loading	TBD
ERQ-008	Lightening protection	TBD

### 5.3.5 Physical Requirements

Key physical requirements for a future weather radar system are listed in Table 5-5.

**Table 5-5. Key Physical Requirements**

System Environmental Requirements		
RQ ID #	Parameters (unit)	Specification (TBD)
PyRQ-001	Number of elements/panel	TBD
PyRQ-002	Number of RFM	TBD
PyRQ-003	Number of IFM	TBD
PyRQ-004	Number of BBM	TBD
PyRQ-005	Panel geometry and size	TBD
PyRQ-006	Panel weight	TBD
PyRQ-007	Power consumption (W)	TBD
PyRQ-008	Cooling method	TBD
PyRQ-009	Structures	TBD

### 5.3.6 Interoperability and Scalability

The term interoperability for this project is specifically used for providing network centric interfaces to the regional and central operation-control centers. For deployment of each ground based fixed radar site with an active phased array weather radar system, networks with FTP or PPP based protocols need to be upgraded with real time protocols and high quality of service to include client/server based weather data transactions between the sites and operations-control centers. Once the network infrastructures of the current systems are upgraded, the future weather sites access and network protocols will be transparent to the legacy weather sites.

The possibility of micro radar sites being sandwiched between the macro radar sites for specific areas was previously discussed. Such configurations might be very useful in special geographical regions, such as “tornado alley”. The micro sites would be equipped with either fewer antenna panels or smaller antenna panels, or both. This is an example of cost-savings scalability made possible with an the active phased array radar design. In addition to the fixed mechanical scalability, active PAR systems provide dynamic EIRP scalability by means of properly selecting the desired beam patterns and elements. The radiated energy can be tailored to form agile beams tuned to observe localized weather phenomena, then re-formed into broad beams for general search operations.



### 5.3.7 Availability

The antenna elements and TRMs are closely integrated in distributed form in active phased array radar systems. This eliminates single point of failures in the RF front-end infrastructure. In addition, performance degradations are expected to be graceful. When a certain percentage of RF components experience failures, built-in test circuits could be used to notify the operations-control center and summon for maintenance. Depending upon the performance threshold established by the operations center, the system can be configured to accommodate various maintenance schedules. Furthermore, the operators can conduct scheduled or event-driven diagnostic or test routines remotely from regional or central operations-control centers. If test results warrant maintenance, technicians can be dispatched to specific radar sites with full understanding of system health status, thus minimizing the mean time to repair. Minimizing the mean time to repair will yield high availability of the systems. Cumulative experience with such a maintenance strategy will reduce the life cycle cost of the systems, while eliminating single point of failures.

### 5.4 Tradeoff Study and Risk Analysis

Conducting a formal risk analysis is beyond the scope of this effort; however, it is possible to do a preliminary tradeoff with respect to certain technical aspects of PAR. An active phased array antenna will be selected over a passive phased array antenna, as justified in terms of the discussion given in the previous sections. High level pros and cons for selecting an active phased array antenna are listed in Table 5-6.

**Table 5-6. Active Phased Array Antenna Pros and Cons**

Pros	Cons
Provides multiple-agile beam forming capability	
Provides scaleable EIRP to each beam	
No mechanical moving parts	
No RF plumbing (wave guides, coaxial cables)	
No need for antenna cooling system	
Fast settling time and beam scanning	
Scaleable panel size and antenna size	
Scaleable RF/IF/BB modules	High number of RF/IF modules
High availability	
Graceful performance degradation	Built in test circuit complexity
Ease of maintenance	
Eliminates single point of failure	

The panel size and geometry of a phased array antenna are very important factors for estimating performance and cost. Since the EIRP requirement for weather Doppler radar is not yet finalized, it is too soon to estimate the number of elements that will determine the panel size. However, it is reasonable to do a preliminary tradeoff study for the panel geometry. There are two categories of panel geometry for phased array antennas: planar and non-planar. Non-planar geometry provide the best design flexibility and adaptability. They can be made to conform to various shapes: spherical, hemispherical, cylindrical, etc. For fixed ground-based radar platforms, a planar geometry with 2, 3 or 4 panels will be selected. High level pros and cons for planar panel active phased array antenna are listed in Table 5-7.



**Table 5-7. Planar Panel Antenna Pros and Cons**

Pros	Cons
Ease of construction	
Stable and fixed tilt angle	
Flexible to adjust panel size (x, y) based on modularized sub-panel (the sub-panel will be a standard size).	
Well defined bore-sight directivity	
Relatively accurate radiation pattern control	Degraded radiation pattern at the edges of panel
Well defined synthesis methods for narrow beam and low side lobe	

The tradeoffs regarding the required number of elements per sub-panel, phase shifters, TRMs, and BBMs are TBD because the required EIRP is itself TBD.

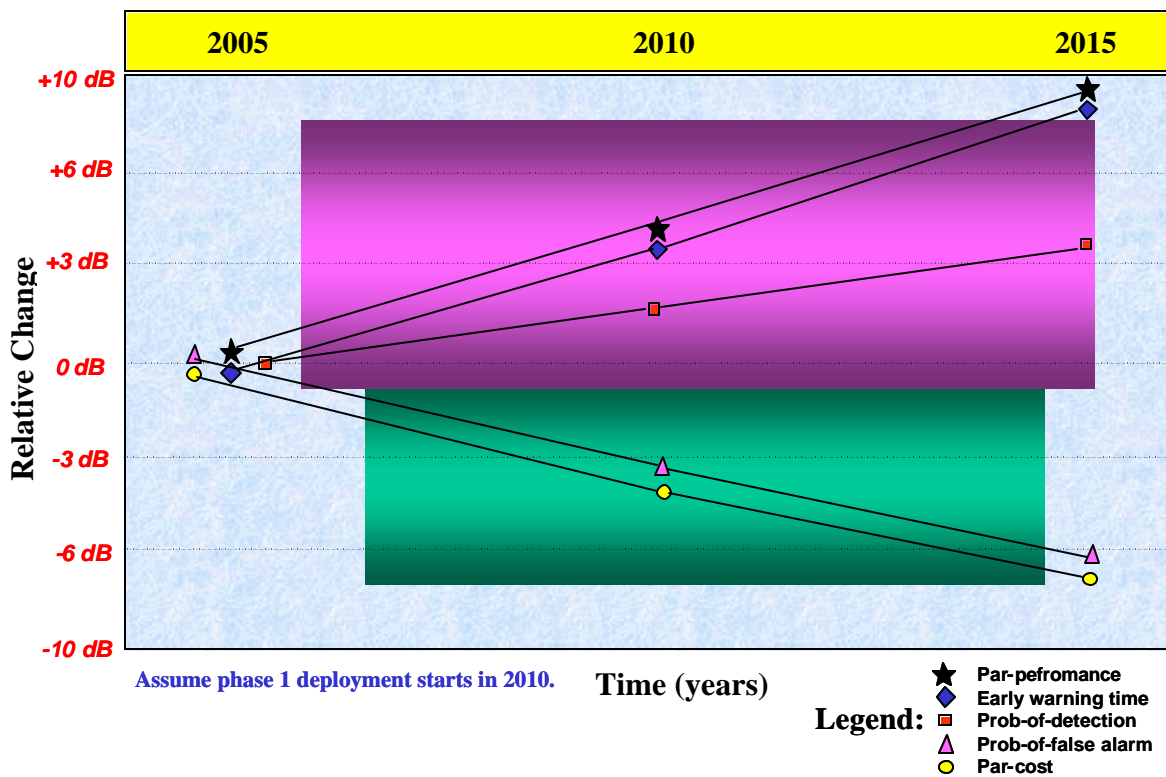




### 5.5 Roadmap of Future Weather Radar

NOAA priorities will serve to formulate a PAR technology roadmap for the evolution of current weather Doppler radar systems such as NEXRAD. In general terms, a major goal of future weather Doppler radar is to increase tornado warning time, the probability of detection, and to decrease the probability of false alarms. However, PAR holds the potential for providing much greater weather science capabilities by virtue of its ability to interrogate a wide variety of meteorological phenomena. Achieving such goals at low cost rules out radical modifications of current operations-control centers where well-tested real-time image processing algorithms, signature recognition algorithms, and weather phenomena models reside. Evolution of the RF front-end infrastructure of the existing NEXRAD weather radar using PAR technology should significantly lower future life-cycle costs. Figure 5-7 shows expected qualitative cost / performance trends for active PAR integrated into future weather Doppler radar systems.

Figure 5-7. Future Weather Radar Roadmap<sup>12</sup>



<sup>12</sup> Note that + 3 dB represents a times 2 improvement, while - 3 dB represents a 50 % reduction.

## 6. Recommendations

In 2003, The National Academy of Science produced a report for NOAA entitled *Weather Radar Technology. Beyond NEXRAD.*<sup>8</sup> *Beyond NEXRAD*, while very top-level, clearly indicates the need to perform in-depth studies to assess the role of active phased array radar for future Doppler weather radar systems. The present report begins the in-depth study process for a comprehensive analysis of PAR and its role for 21<sup>st</sup> century weather Doppler radar applications.

Several important recommendations can be quoted from *Beyond NEXRAD* that are consistent with the findings of the present work:

- *“Adaptive waveform selection, which may even be applied to present systems, and agile beam scanning strategies, which require an electronically scanned phased array system, should be explored to optimize performance in diverse weather*
- *The technical characteristics, design, and costs of phased array radar systems that would provide the needed rapid scanning, while preserving important capabilities such as polarization diversity, should be established.*
- *The next generation of radars should be designed as part of an integrated observing system aimed at improving forecasts and warnings on relevant time and space scales.*
- *Weather surveillance needs should be evaluated by geographic region to determine if a common radar system design is appropriate for all regions.”*

The latter two points are especially notable in that *Beyond NEXRAD* calls for improving forecasts and warnings on relevant time and space scales. The scalability of active PAR supports this need implicitly.

Based on the present limited study, the following recommendations concerning phased array radar technology and future weather Doppler radar warning systems include:

- A fundamental examination of basic weather science issues to drive out the complementary roles of phased array and traditional approaches to weather Doppler radar.
- In-depth analysis to understand the importance of real-time frequency diversity, polarization diversity, sampling rate diversity, and waveform diversity for new weather Doppler radars.
- The use of planar active phased array antennas in future weather Doppler radar systems.
- The use of real-time adaptive beam forming and beam steering techniques in future weather Doppler radar systems.
- The use of real-time, multiple transmit-receive beams (simultaneous) with independent beam forming capabilities in future weather Doppler radar systems.
- An in-depth analysis of real-time networking concepts to fully exploit the potential of PAR for true factor of two severe weather early warning improvements.
- The definition of future weather radar systems architecture concepts where re-locatable micro-radar platforms operate near traditional (or existing) radar platforms.



The present quick-look study supports the view that active phased array radar technology could engender future weather Doppler radar systems with important cost and performance attributes, including:

- Life-cycle costs reduced by a one-half those of current systems. Large contributions of the life-cycle cost reduction will come from elimination of costly single point of failure parts.
- Increased systems availability, with ease of maintenance due to graceful degradation of performance.
- Important technical advantages that can support factor of two improvements in key severe weather early warning such as warning time improvement, increased probability of detection and decreased probability of false alarm.

Figure 6-1 shows the logical extension of the present work to provide a definitive assessment of active phased array Doppler radar for weather applications. The guiding goals and requirements defined by NOAA NWS for its 2005-2020 Doppler radar systems drive the study approach. Current NEXRAD capabilities are well-known, as are the costs for the products produced by the NEXRAD system. It may be assumed that current NEXRAD technical capabilities need to be met or exceeded. The cost for providing such capabilities via PAR must be derived by in-depth study of the current COTS applications and markets for PAR technology. There are at least ten vendors that currently produce such systems or components. Cost / benefits trades, coupled with potential concepts of operation for a PAR-based system, will then drive out the key recommendations of the study.

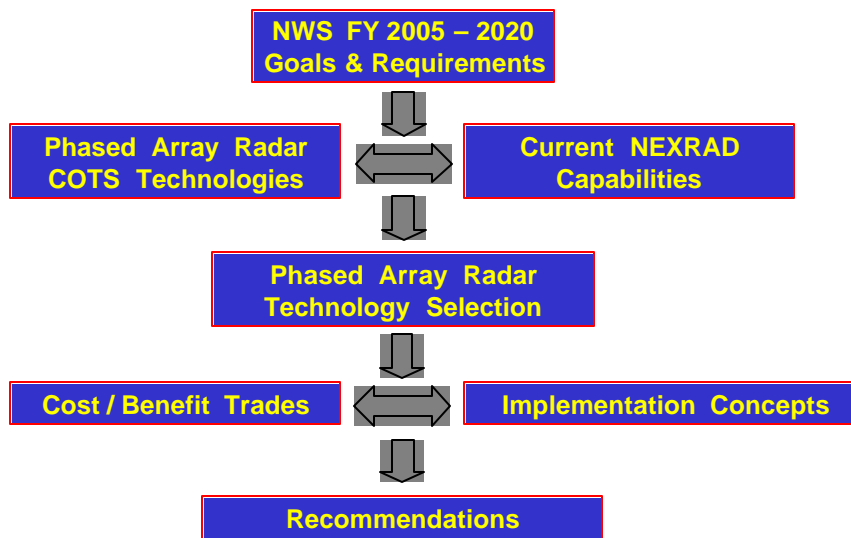


Figure 6-1. Top-Level Process for an In-Depth Study of Active PAR

An extensive, critical assessment of the COTS PAR commercial market will provide the logical basis and fundamental data for a traditional cost / benefit analysis.

The possible benefits and cost reductions for an active phased array Doppler weather radar system accrue from several factors, all of which must be critically examined and substantiated by domain experts. These factors include



significant reductions in single-point-of-failure components, graceful system performance degradation, highly predictable system maintenance schedules, and elimination or reduction of mechanical components.

In addition, the technical potential of COTS PAR for Doppler weather radar science is enormous. This is due to the fundamentally different means by which radar transmission and reception is accomplished in a PAR system. Factor of 2 improvements for tornado early warning are credible, but must be substantiated by detailed technical analysis by weather science experts.

A major study objective would be to quantify PAR weather Doppler radar costs and benefits from the perspective of systems architecture and operations, and to understand the specific improvements to radar products that ultimately are provided to meteorological and weather science users.

## 7. Acronyms

az	azimuth
ADC	Analog to Digital Converter
APAR	Active Phased Array Radar
BBM	Base Band Module
cm	centimeter
C	Centigrade temperature
CW	Continuous Wave
dB	decibel
deg	degree
DSP	Digital Signal Processing
DAC	Digital to Analog Converter
DSP	Digital Signal Processor
el	elevation
EIRP	Effective Isotropic Radiated Power
ft	foot
FEMA	Federal Emergency Management Agency
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
FTP	File Transfer Protocol
g	acceleration due to gravity
GaAs	Gallium Arsenide
GHz	Gigahertz
GOES	Geostationary Operational Environmental Satellite
G/T	Gain-to-system-noise-Temperature ratio
JSTARS	Joint Surveillance and Target Attack Radar System
IEEE	Institute of Electrical and Electronics Engineers
IFM	IF Module
IP	Internet Protocol
I/Q	Inphase/Quadrature
kHz	kilohertz
km	kilometer
kW	kilowatt
K	Kelvin temperature
LNA	Low Noise Amplifier
m	meter
MIPS	Millions of Instructions Per Second
MHz	megahertz
MMIC	Monolithic Microwave Integrated Circuit

## NOAA Future Weather Doppler Radar Study



MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NM	Nautical mile
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Lab
NPOESS	National Polar-orbiting Operational Environmental Satellite System
PA	Power Amplifier
PAA	Phased Array Antenna
PAR	Phased Array Radar
PPAR	Passive PAR
PPP	Point-to-Point Protocol
POES	Polar-orbiting Operational Environmental Satellite
PRT	Pulse Repetition Time
RF	Radio Frequency
RFI	Request For Information
RFM	RF Module
RFP	Request For Proposal
RX	receive
s	second
SAR	Synthetic Aperture Radar
SSPA	Solid State Power Amplifier
TBD	To Be Determined
TRM	Transmit/Receive Module
TRMM	Tropical Rainfall Measuring Mission
TS	Tornado System
TVS	Tornadic Vortex System
TWTA	Traveling Wave Tube Amplifier
TX	transmit
UAV	Unmanned Aerial Vehicle

## 8. Appendices

### Appendix A: Ball Aerospace Presentations and Documents

NOAA, Aerospace and Ball held a meeting to discuss phased array radar technology on January 16, 2004. Ball presented the following charts to describe their capabilities in phased array antenna design, test and manufacturing.



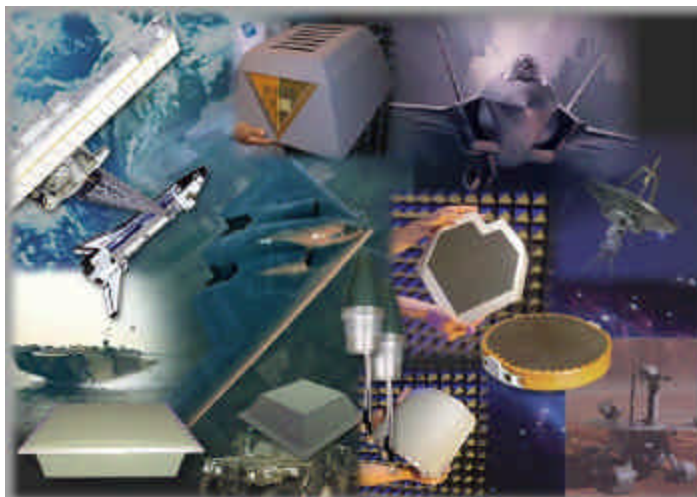
## Antenna Systems and Technologies (AST)

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1



### Ball antennas cover a wide range of technologies

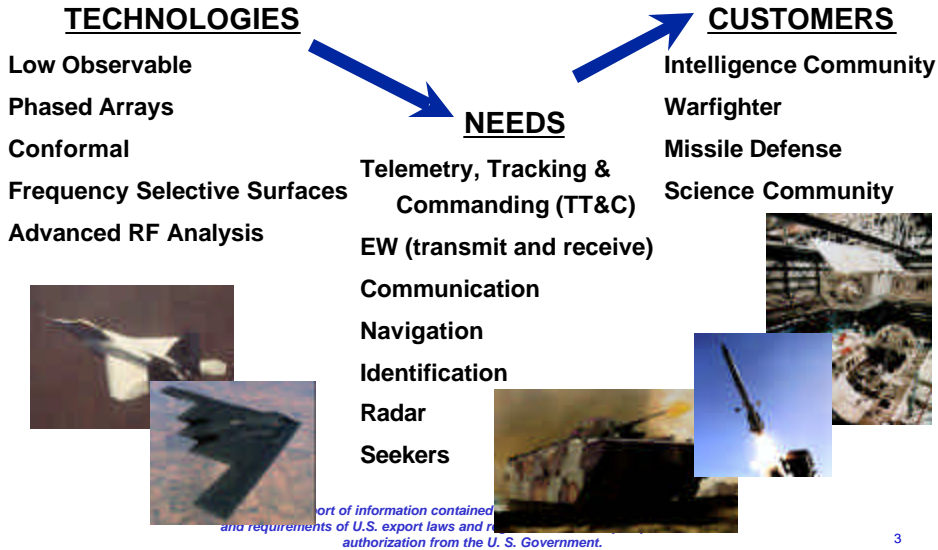


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2



## Ball antenna technologies meet needs of multiple customers



3



## Phased Arrays

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4



## The phased array antenna is now used commercially

**AIRLINK®  
Aeronautical  
Satellite  
Products**



**AIRLINK®  
Low Gain**

**AIRLINK®** products are antenna systems and related avionics designed to provide in-flight telephone, fax and data transmission. **AIRLINK®** systems provide dependable communication services to general aviation, air transport and government aircraft.

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## AIRLINK® Secure Satcom System adds STU-III interface



The Secure **AIRLINK®** Aeronautical Satellite Communications System offers worldwide, reliable communications from an aircraft, or from the ground to the aircraft, in secure or non-secure modes. This **AIRLINK®** product provides multiple channels for in-flight telephone, fax, data and limited-motion video using the Inmarsat satellite system.

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## Spaceborne Imaging Radar C (SIR-C) antenna aids imaging



SIR-C uses synthetic aperture radar beams to map the Earth from space. Synthetic aperture radar technology provides day and night measurements through cloud cover. Ball has supported five NASA missions: SEASAT, SIR-A, SIR-B and two flights of SIR-C.

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## Shuttle Radar Topography Mission (SRTM) maps the earth



Launched in February 2000, SRTM returned images of 80 percent of the Earth's land surface for the Department of Defense. Data will be used to create 3-D topographical maps with a vertical resolution of better than 16 meters.

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## Background on Existing S-band antennas

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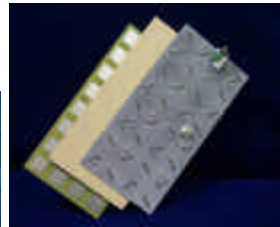
## Ball has a long history in S-band phased arrays



Navy S-band



RDFA



IR&D



MGT *Export or re-export of information contained herein may be subject to restrictions and requirements of U.S. export laws and regulations, and may require advance authorization from the U. S. Government.*



BCW

10



## Navy S-band phased arrays are targeted towards future ship applications



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## Current Navy S-band antenna creates three receive-only beams



- 2.2-2.4 GHz bandwidth
- Shipboard environment
- DACS soft handoff between array faces

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12

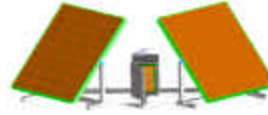


## Existing S-band phased array has special features

### Thin and Flat

Can be embedded in Ship Superstructure

- Subarray panel is 1.5" thick
- Compatible with composite or metal



### LO Aperture

Provides low RCS with minimal loss in efficiency. Achieves DDX RCS requirements.

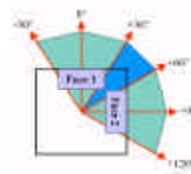
- FSS integrated at the element level eliminates FSS Radome
- RCS measured at Ball and NAWC– meet DDX requirements



### DACS Correlator

Combines energy from 2 adjacent sides for around-the-corner gain improvement. Arrays can be 33% smaller. Array faces do not need to be co-located.

- Handoff demonstrated during satellite tracking



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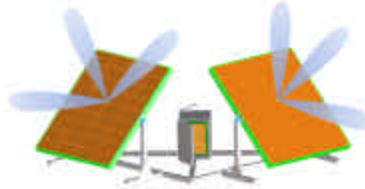


## Existing S-band phased array has special features

### 3 Simultaneous Beams per Array Face

Allows for multiple tracking and multifunction operation. More beams could be added.

- Demonstrated with satellite tracking
- Stereo DSP downlink demonstrated



### EMI Protection

Protected from shipboard EMI environment during operation (SPS-48, TAS, INMARSAT, SPS-49, SPY-1). Protected for in-band survival.

- EMI protection analyzed, designed and tested at Ball
- EMI protection tested at Dahlgren
- EMI protection tested on the ship



### State-of-the-Art, Low Cost, Producing Hardware

Dispels the myth that Phased Arrays must be expensive. Low cost materials/parts/processes. Pick and place.

- Circuit board technology
- room temperature low pressure lamination
- low cost "cell phone technology" components

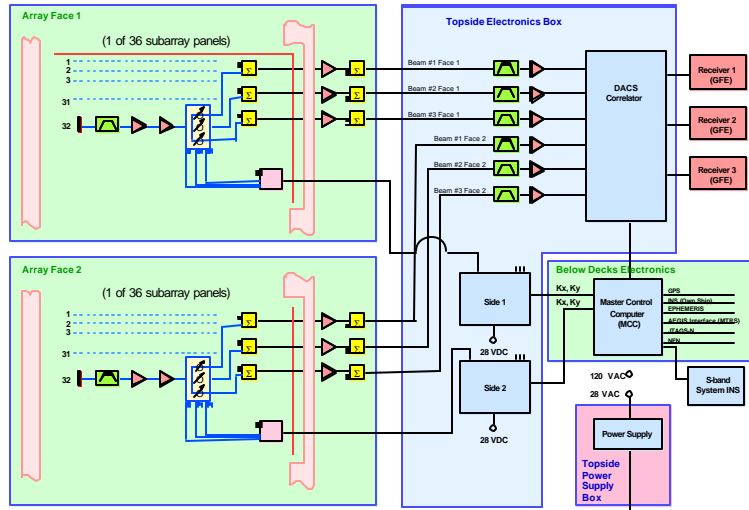


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14



**Block diagram shows existing S-band functions**

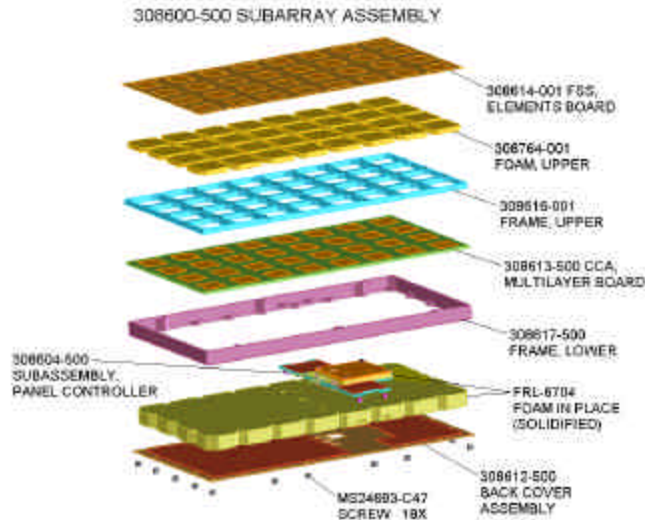


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15



**Exploded subarray view shows construction**

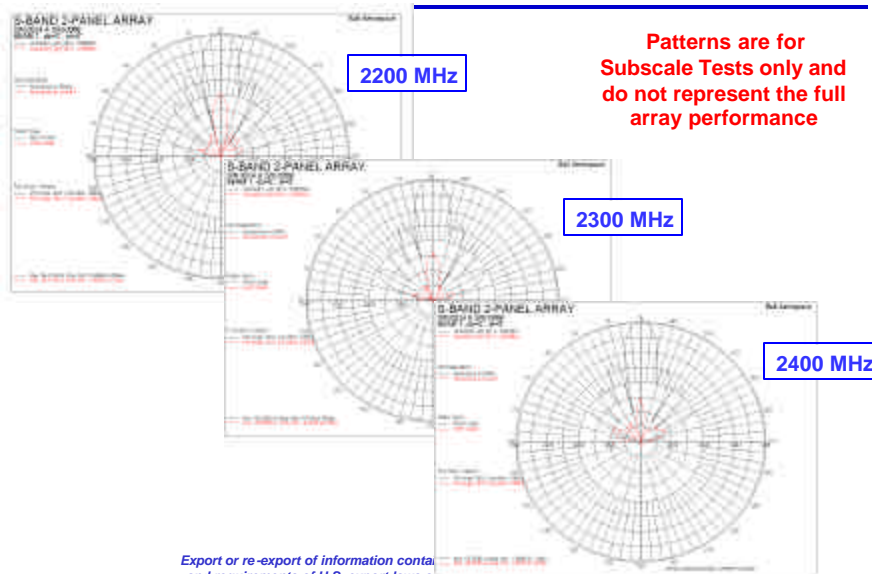


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16



### Graphs show 2-panel gain at broadside

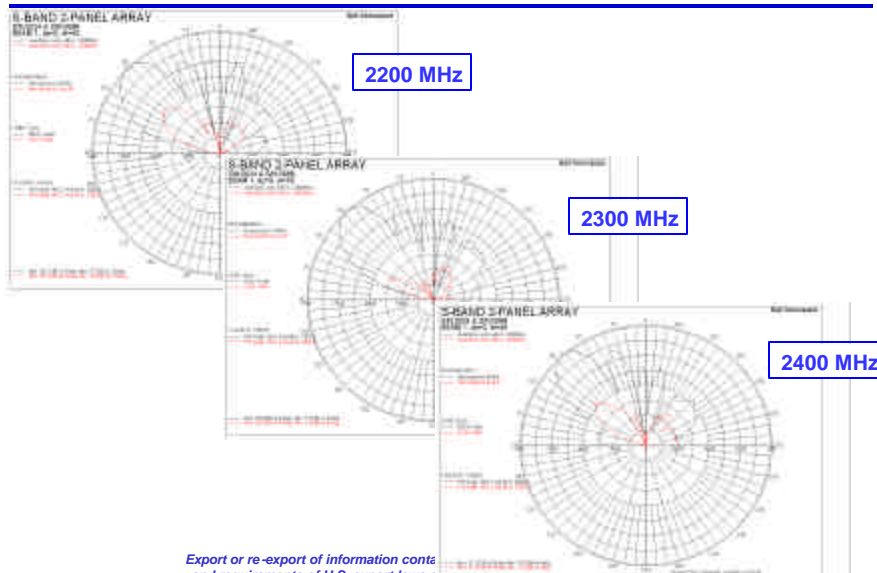


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### Graphs show 2-panel gain at 45° elevation



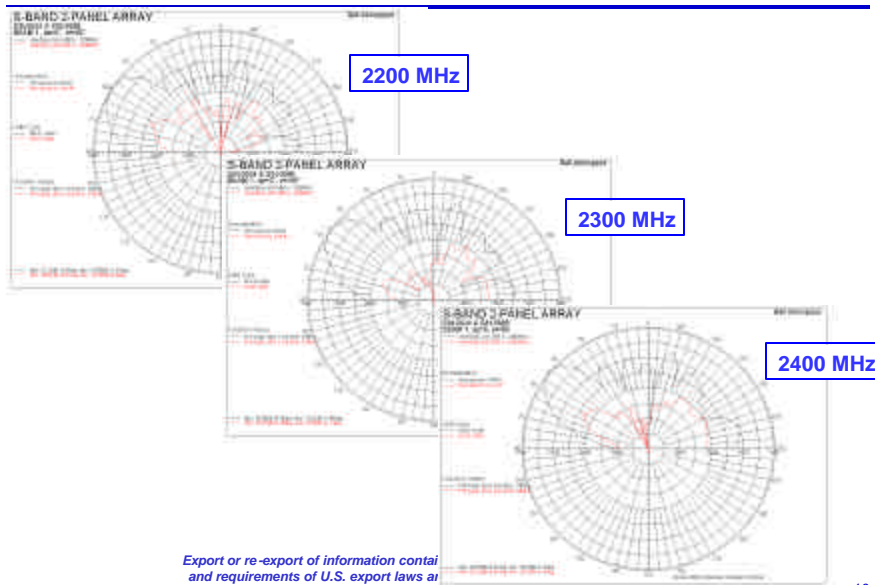
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## Graphs show 2-panel gain at 60° elevation



## View shows antennas on the USS Lake Erie

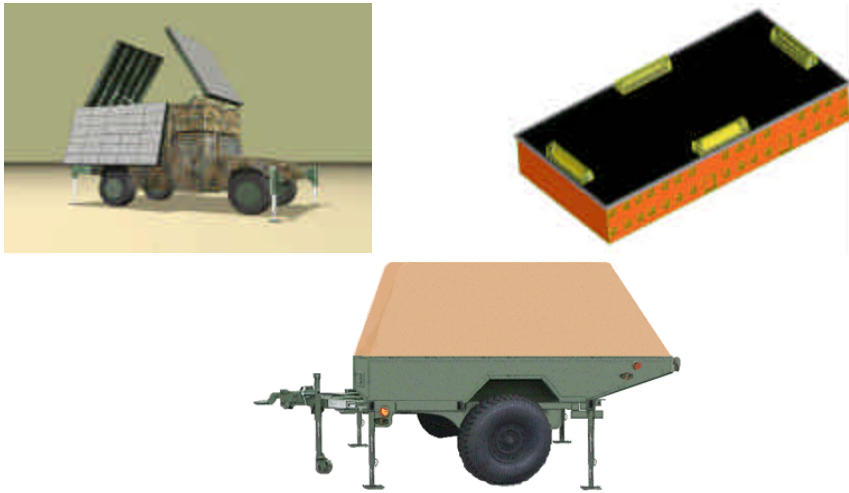


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### Concepts exist for other S-band phased array applications

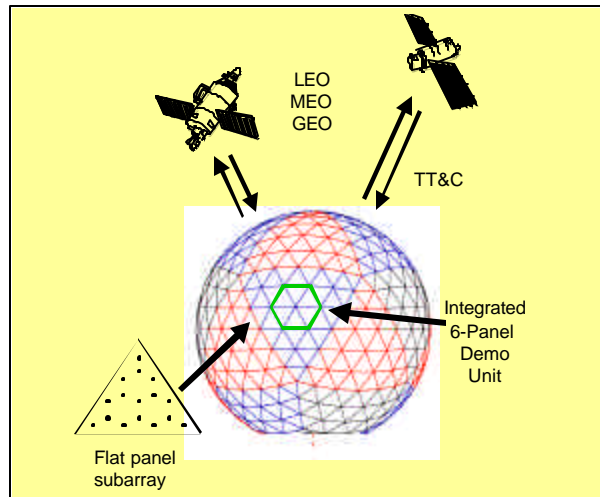


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21



### The Phased Array for TT&C (PAT) program is developing a transmit/receive array w/ up to 8 beams



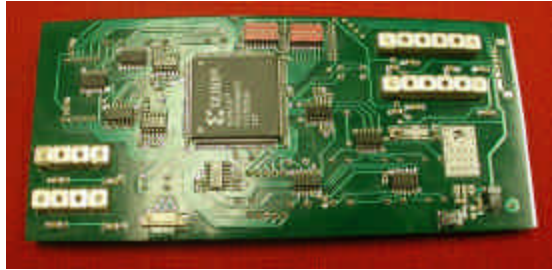
Export or re-export of information contained herein may be subject to restrictions and requirements of U.S. export laws and regulations, and may require advance authorization from the U. S. Government.

22





## Module from PAT program provides two beams for transmit and two beams for receive



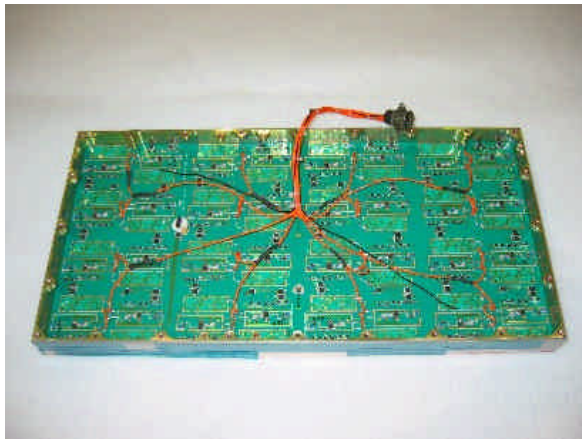
- 1.75-1.85 GHz Transmit
- 2.2-2.3 GHz Receive
- One module per element mounted perpendicular to array face
- Not a low profile array solution

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23



## Modified Navy S-band panel recently demonstrated transmit operation



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24



**Projections for use in Weather Radar**

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25



**NEXRAD is used as a reference design**

NEXRAD	low	middle	high
Frequency (MHz)	2700	2850	3000
Transmit Power (kW peak)	750	750	750
Transmit power (W average)	300		1300
Transmit output to antenna loss (dB)	2	2	2
Pulse width (us)	1.57		4.5
PRF (Hz)	318		1304
Antenna diameter (ft)	28	28	28
Gain(inc. radome loss)		45.5	
Beamwidth (deg)		0.925	
Radome two way loss (dB)		0.24	
System noise temperature (K)		540	
EIRP (dBm peak)		132.25	
G/T (dB/K)		18.18	

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**Phased array projections are based on a cylindrical aperture**



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27



**Projected performance for phased array seeks to match PG/T performance**

Phased Array (cylindrical shape)	low	middle	high
Frequency (MHz)	2700	2850	3000
Antenna diameter (ft)	28	28	28
Antenna height (ft)	28	28	28
Effective area (ft <sup>2</sup> )	678.96	678.96	678.96
Wavelength (feet)	0.36	0.35	0.33
Azimuth Beamwidth (deg)	0.78	0.74	0.70
~ Number of elements (total)		82605	
~ Number of active elements		27535	
Directivity (dB) maximum	48.08	48.55	48.99
Directivity (dB) at 45 degrees elevation	45.97	46.44	46.88
Non-ohmic losses (dB)	0.75	0.75	0.75
System noise temperature (K)	300	300	300
G/T (dB/K peak)	20.45	20.92	21.36
G/T (dB/K) at 45 degrees elevation	18.34	18.81	19.26
Power per element (W peak)		10	
EIRP (dBm peak)		132.32	
EIRP (dBm) at 45 degrees		130.21	
Prime power (kW peak)		1101.40	
Prime power (W avg)	440.56		1909.09

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28

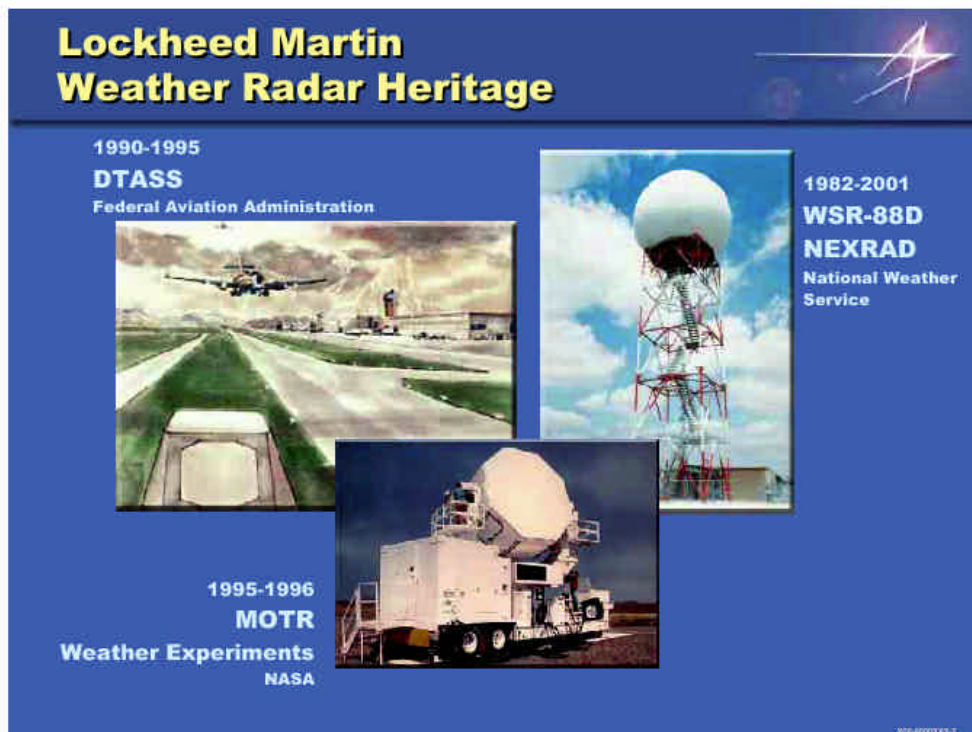
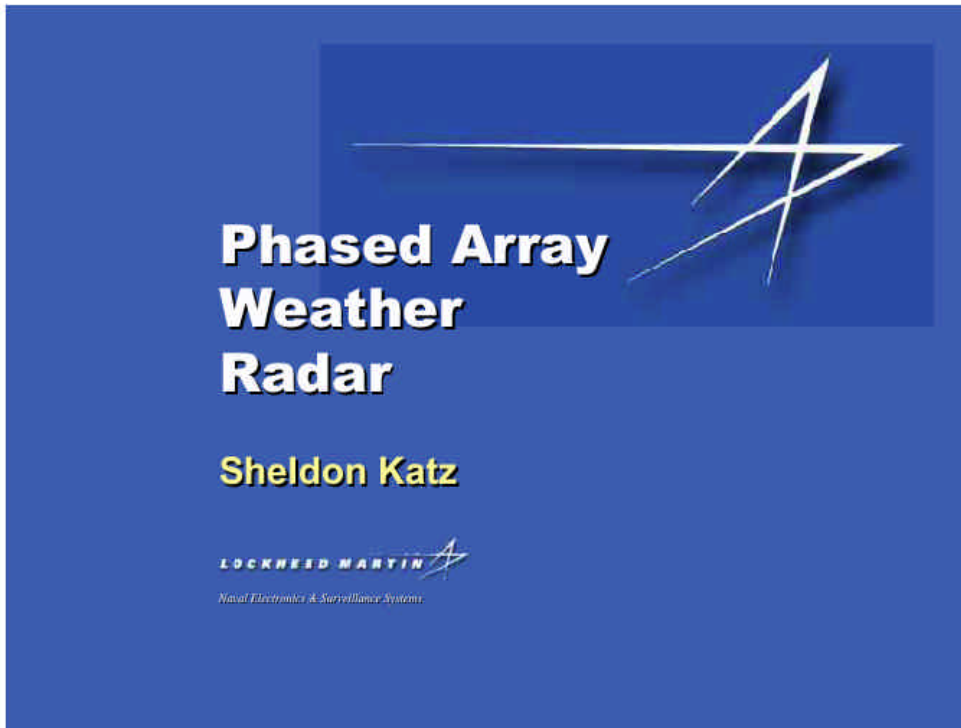


**Projected performance for planar phased array has similar performance**

Phased Array (single panel)	low	middle	high
Frequency (MHz)	2700	2850	3000
Antenna width (ft)	28	28	28
Antenna height (ft)	28	28	28
Effective area (ft <sup>2</sup> )	784.00	784.00	784.00
Wavelength (feet)	0.36	0.35	0.33
Azimuth Beamwidth (deg)	0.68	0.64	0.61
~ Number of elements (total)		26294	
~ Number of active elements		26294	
Directivity (dB) maximum	48.70	49.17	49.62
Directivity (dB) at 45 degrees elevation	46.59	47.06	47.51
Non-ohmic losses (dB)	0.75	0.75	0.75
System noise temperature (K)	300	300	300
G/T (dB/K peak)	21.07	21.54	21.99
G/T (dB/K) at 45 degrees elevation	18.96	19.43	19.88
Power per element (W peak)		10	
EIRP (dBm peak)		132.74	
EIRP (dBm) at 45 degrees		130.64	
Prime power (kW peak)		1051.76	
Prime power (W avg)	420.70		1823.04

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Appendix B: Lockheed Martin Presentations and Documents






## Lockheed Martin Weather Radar Heritage


**1990-1995**  
**DTASS**  
Federal Aviation Administration



**1982-2001**  
**WSR-88D**  
**NEXRAD**  
National Weather Service



**1995-1996**  
**MOTR**  
Weather Experiments  
NASA



300-40000000-2

## Lockheed Martin Weather Radar Heritage

**1996-2001**  
**Tactical Environmental Processor**  
Office of Naval Research and PMS400



**2000-2001**  
**Dual-Use, Low-Cost Plastic Module**  
Office of Naval Research



**2000-2002**  
**National Weather Testbed**  
Office of Naval Research



**Wind Profiler**  
Syracuse, New York



300-40000000-2

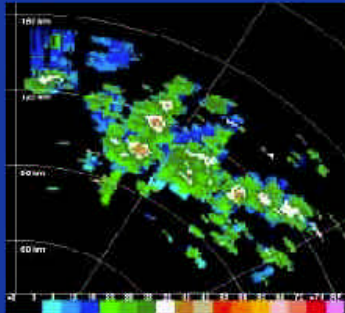


## TEP Provides Accurate Reflectivity Measurements

**Goal** • Validate Basic Spectral Moments from SPY-1 with NEXRAD

**Result** • SPY-1 Matches NEXRAD Reflectivity, Velocity, Spectrum Spread  
 • SPY-1 Demonstrates Better Temporal Resolution

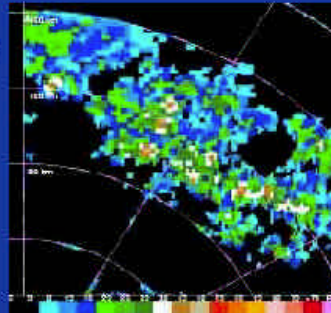
### SPY-1 vs. NEXRAD Composite Reflectivity Hurricane Fran Remnants



**SPY-1 (Single -Pulse)**

NOTE: Threshold Applied to SPY-1 Reflectivity Map Above Noise Floor

Data Collected on SPY Weather Experiment



**NEXRAD (~100-Pulse)**

880-6000XXX-4

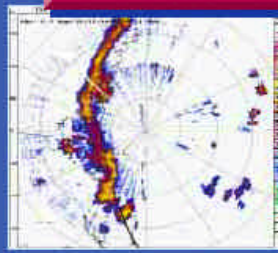
## Demonstrated TEP Performance

### Cloud Base/Tops

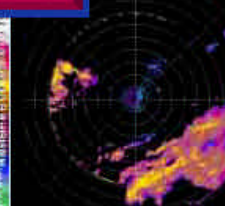


Cloud Tops / Bases  
Mar 18, 1997

### Hazardous Weather



Nighttime Squall off JAX  
Sept 10, 1999

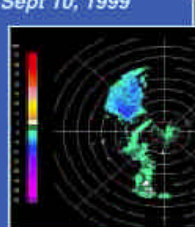


Hurricane Dennis  
August 30, 1999

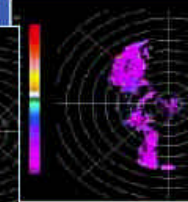
### Wind Mapping



Winds off JAX  
Sept 10, 1999



Radial Velocity



Spectrum Width

880-6000XXX-4



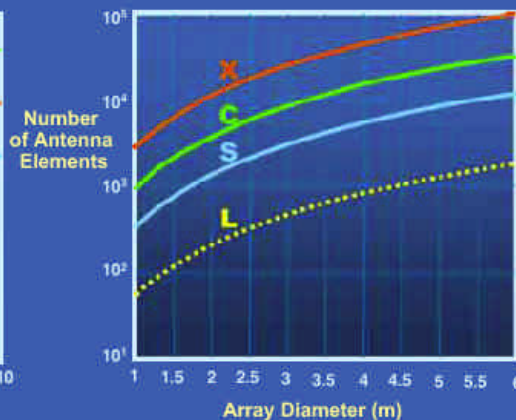
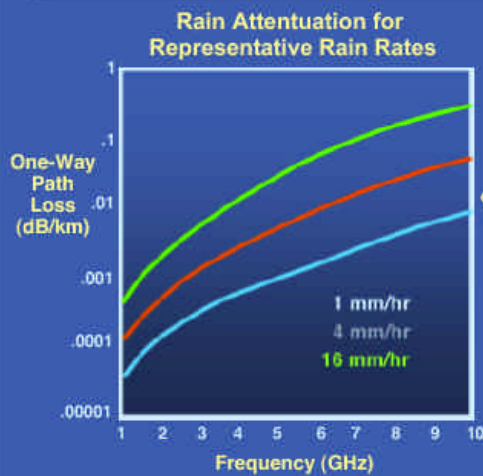
## Benefits of Phased Array Radar for Weather Sensing

- Rapid update of developing weather events
- Improved spectral moment data quality
- Tailoring of radar scan pattern for local obstructions
- Improved ground clutter cancellation
- Improved ability to recover overlaid echoes
- Improved compensation for reflectivity biases

610-0000003-6

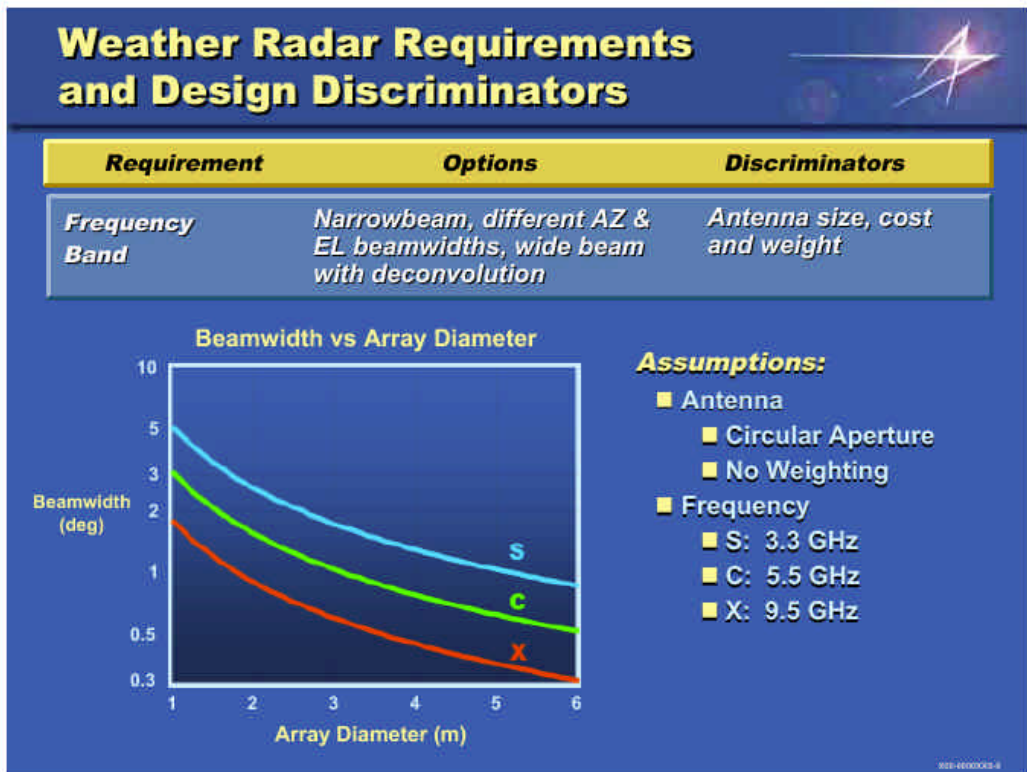
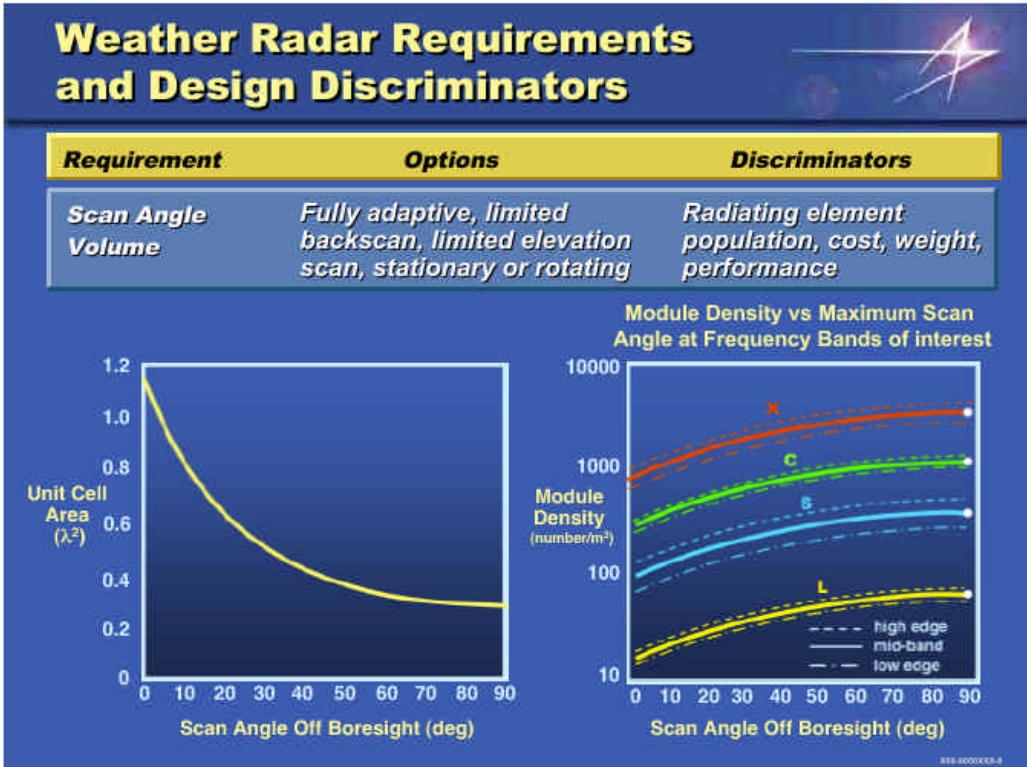
## Weather Radar Requirements and Design Discriminators

Requirement	Options	Discriminators
Frequency Band	S, C, X	Attenuation, antenna size, cost & weight, beamwidth



610-0000003-7

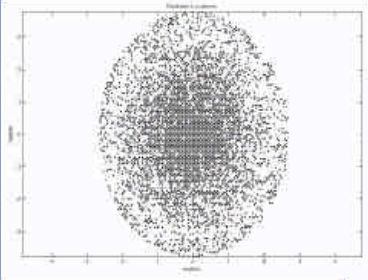




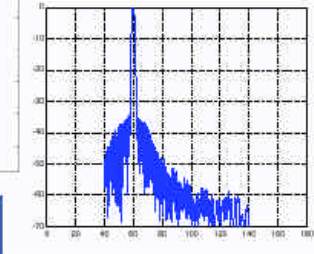
## Weather Radar Requirements Drivers

Requirement	Options	Discriminators
<b>Sidelobe Levels</b>	<i>Control via weighting on transmit or receive or both, thinned aperture, active array</i>	<i>Beamwidth, cost, sidelobe performance</i>

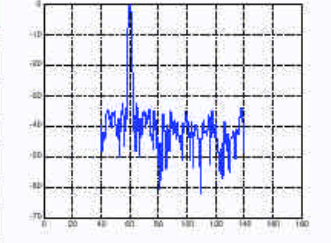
**Thinned Array Face**



**Fully Populated Array  
35 dB Taylor Taper**



**52% Thinned Array  
35 dB Taylor Taper**

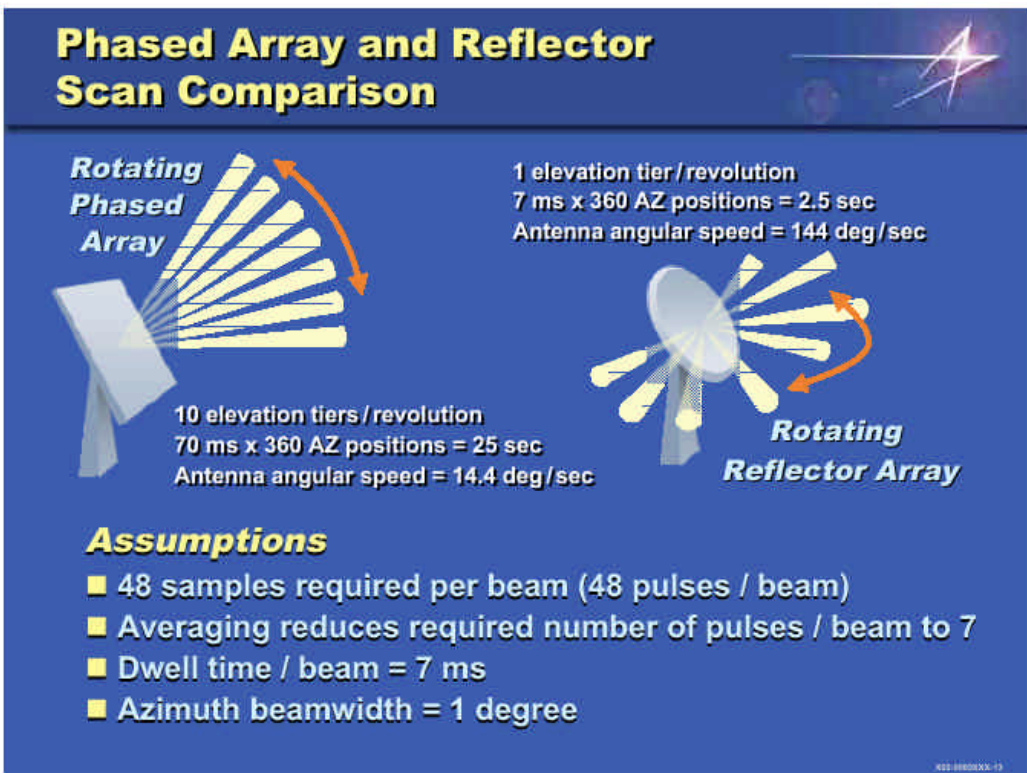
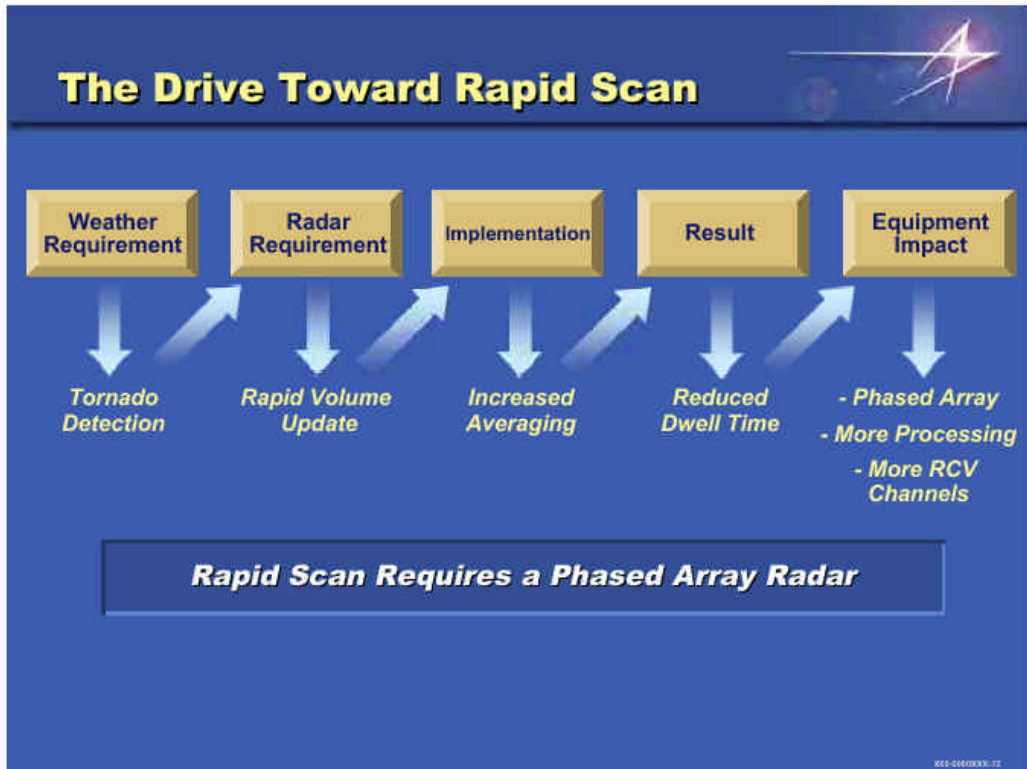


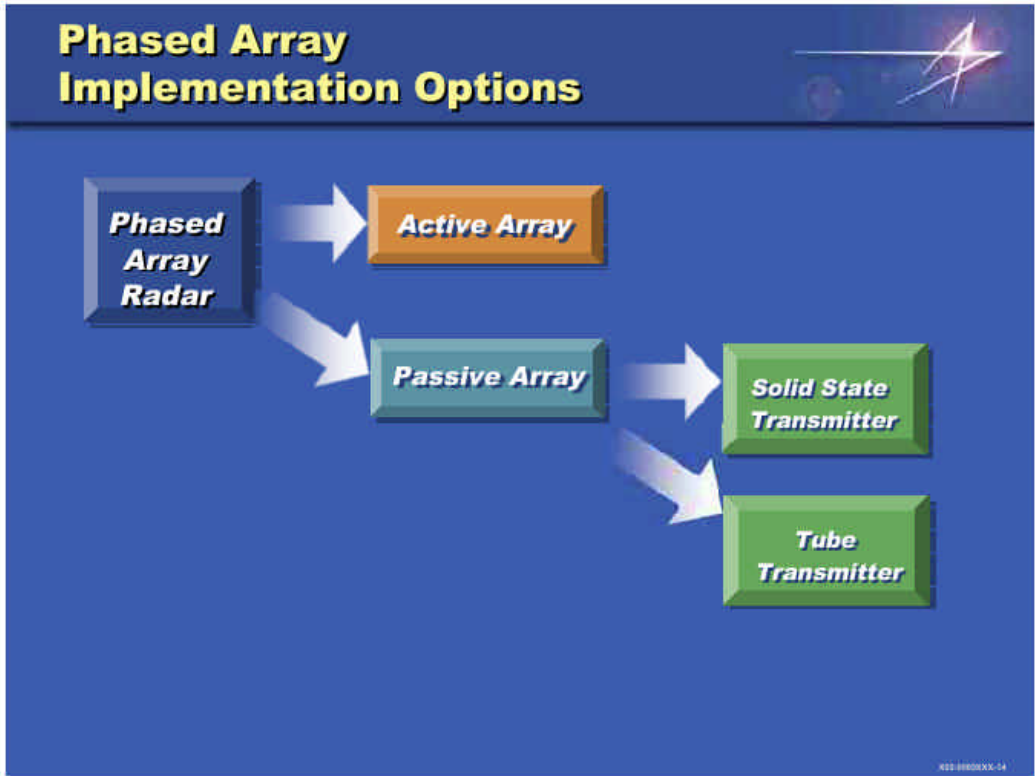
NWS-0000000X-10

## Weather Radar Requirements Drivers

Requirement	Options	Discriminators
<b>Range Resolution</b>	<i>250 m to 1000 m</i>	<i>Weather phenomena of interest, rapid scan, sigpro capability</i>
<b>Ground Clutter Suppression</b>	<i>Signal processing techniques, phased array or reflector, solid state or tube transmitter</i>	<i>System stability, antenna sidelobes, electronic scan for discrete avoidance, shaped beam, backscan</i>
<b>Dual Polarization</b>	<i>Transmit elliptical, receive H &amp; V, transmit linear, receive copolar &amp; cross-polar components</i>	<i>Polarization isolation/purity, H/V pattern match</i>
<b>Increased Reliability</b>	<i>4, 2, or 1 faced Phased Array Radar, AZ motion scan only, solid state transmitter</i>	<i>Reduced antenna motion, eliminate single point of failure, increased component reliability</i>

NWS-0000000X-11





### Phased Array Advantages by Array Configuration

Advantages	Active Array	Passive Array	
		Solid State TX	Tube TX
Flexible Scan	+	+	+
Rapid Scan	+	+	+
System Stability	+	+	
Graceful Degradation	+	+	
Reliability	+	+	
Low Peak Power (siting)	+	+	
High Duty Factor	+	+	
Low Transmit Losses	+		
Low System Noise Temperature	+		



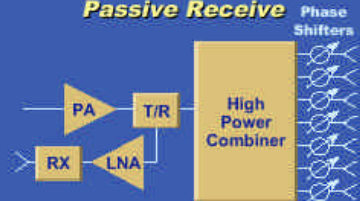
## Phased Array Disadvantages by Array Configuration

Disadvantages	Active Array	Passive Array	
		Solid State TX	Tube TX
Beam Broadening Off Axis	—	—	—
Polarization Purity Off Axis	—	—	—
Single Point of Failure			—
High Peak Power			—

833-0000XX-16

## Active Array Technology

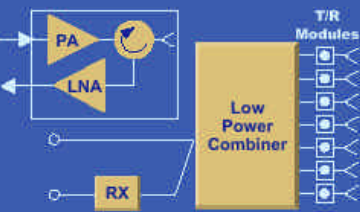
**Centralized Transmitter  
Passive Receive**



**Characteristics**

- Very High Power RF Tube Technology
- Waveguide Energy Distribution
- High Receiver Losses
- High Transmit Losses

**Active Array Antenna**



**Characteristics**

- Transmit/Receive Modules are Key Components
- Transmit & Receive Electronics at Each Element
- Low Receiver Losses
- Low Transmit Losses

**Active Array Technology Decreases System Loss**

833-0000XX-17

## Active T/R Modules

**Antenna Costs**

Structure  
Cooling  
Power Control

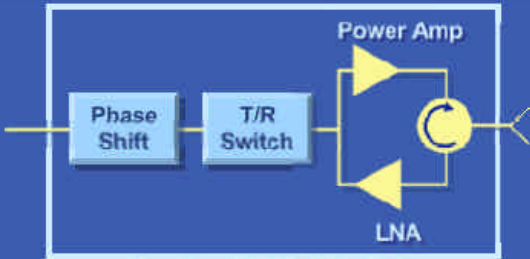
T/R Module

↓

**T/R Module**

Packaging  
Assembly & Test

MMIC Components  
Other



**Typical T/R Module Block Diagram**

- MMIC's are major cost drivers
- Advanced device technologies show promise for improved power density resulting in decreased cost for antenna

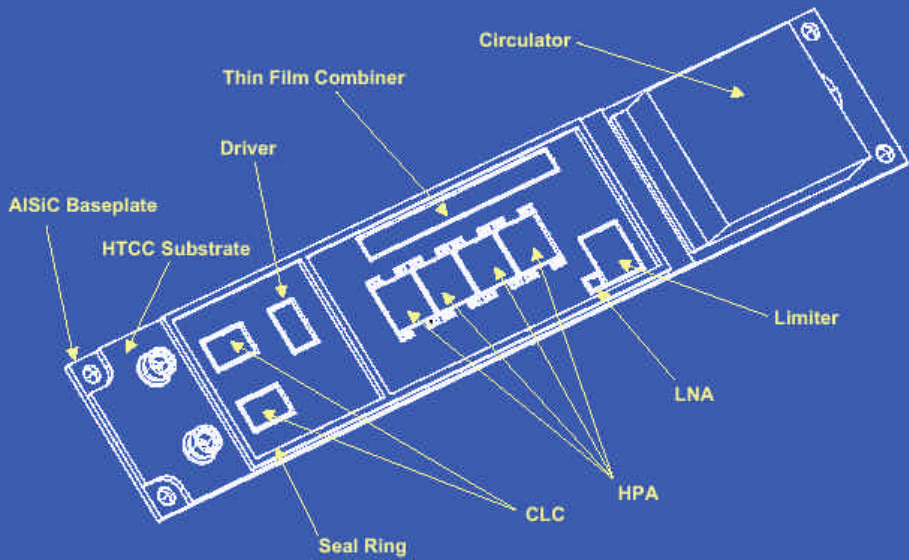
802-0000XX-18

## T/R Module Power Amplifier Semiconductors

Frequency Band	L	S	C	X	Ka
<b>Existing</b>					
Silicon	High Power	Medium Power			
Gallium Arsenide	Low Power				Low Power
<b>Developmental (Potential)</b>					
<5 Years Silicon Carbide	High Power			Medium Power	
>5 Years Gallium Nitride	High Power				Medium Power
<b>Other Considerations:</b>					
	<ul style="list-style-type: none"> <li>■ Cost (Device and Module)</li> <li>■ Efficiency</li> <li>■ Reliability</li> </ul>				

802-0000XX-19

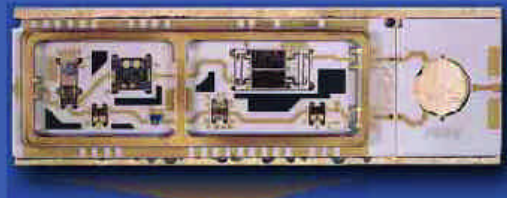
## Example of T/R Module



## Packaging Advances

- *Size reduction potential of HDI packaging technology compared to other conventional packaging technologies*

**Conventional Packaging Technology**

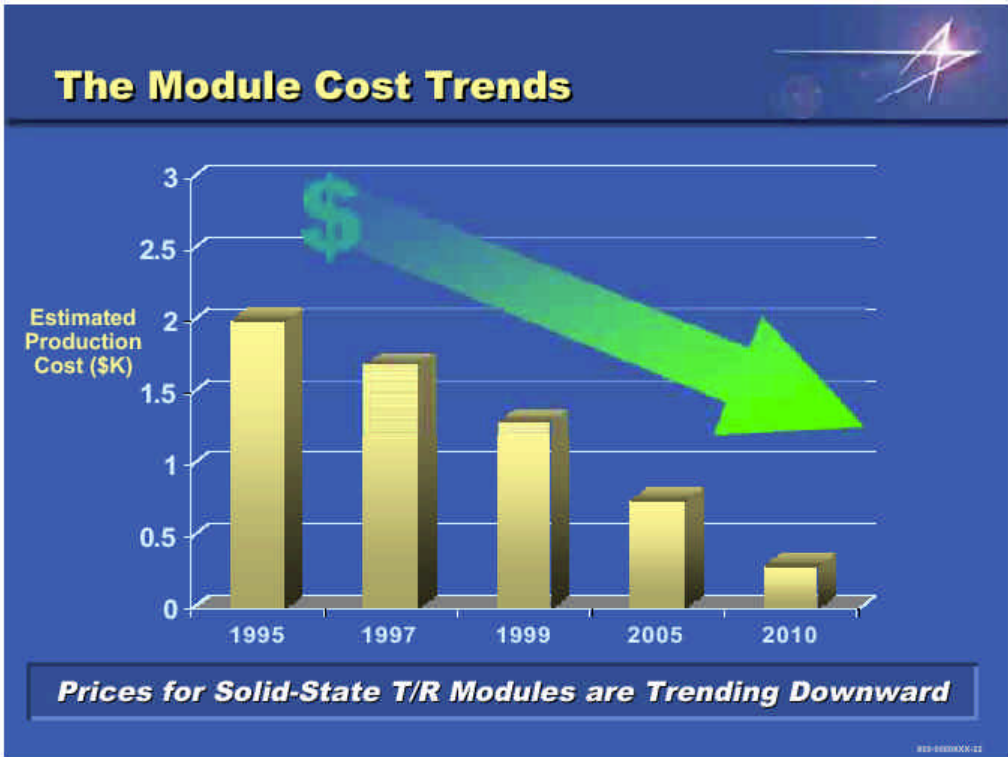


**Ceramic HDI**



**HDI**

*Overall size of module kept the same as conventional packaged module due to fixture re-use*



### Summary

- *Rapid scan of meteorological events requires a phased array*
- *Cost of solid state T/R module based arrays is decreasing*
- *Alternatives to T/R module based arrays are also part of the trade space*
- *Phased array weather radar trade space provides many design options*
- *Scientific and user community must set priorities on weather radar requirements*

813-4110XXX-23





## Appendix C: CEA-FAR Presentations and Documents



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TECHNOLOGIES, INC.



# CEA-FAR ACTIVE PHASED ARRAY RADAR TECHNICAL OVERVIEW

## CEA TECHNOLOGIES PTY LIMITED

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CEA-FAR Technical Overview

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## 1. SYSTEM OVERVIEW

### 1.1 INTRODUCTION

CEA-FAR is a new concept in radar technology. It provides a programmable, scalable active phased array radar system that can be configured to meet customer application performance and budget constraints.

The system is characterised by its modularity, programmability and scalability, with the smallest system being man portable and the largest system suitable for land and maritime wide area surveillance applications. This scalability is primarily achieved by a modular active antenna design in which the array is comprised of a number of static faces (nominally 6) to provide 360-degree surveillance, each made up of a number of tiles (the basic building block of the antenna). Each tile is just 13.3 inches square and 8 inches deep and is designed for field replacement if required. Increasing the size of the array brings performance increases in both transmit and receive beamwidths, and in the level of transmit RF generated. No additional processing equipment infrastructure is necessary to support arrays over the range of applicable sizes.



Figure 1 - CEA-FAR Antenna Tile (Exposed Rear View)



Figure 2 - CEA-FAR Panel 1 (Front View)

The CEA-FAR radar system is typically supplied as an integrated radar system using the CEA-MIDDS data fusion workstation to provide radar control, operational display, simulation and modelling, system optimisation and fusion of other surveillance and link based sensors. The effectiveness of the CEA-FAR radar is based in its array programmability and waveform/signal processing flexibility. This allows the radar to be optimally and dynamically adapted to meet the evolving demands of the environment and operational scenario.

<sup>1</sup> A CEA-FAR Panel is a 2 x 2 array of CEA-FAR Antenna Tiles.



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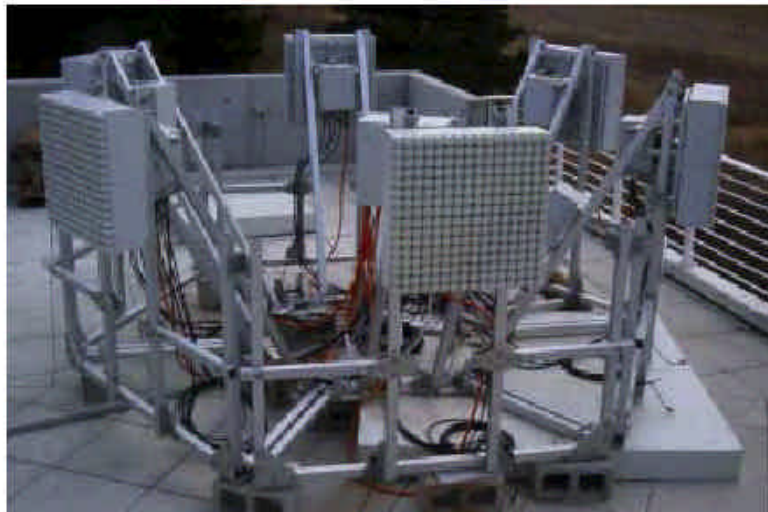
CEA-FAR Technical Overview

System Overview

## 1.2 AEROSPACE, LAND AND MARITIME APPLICATIONS

CEA-FAR as applied to aerospace, land and maritime applications is an S Band Active Phased Array Multi-Function Radar designed to simultaneously provide:

- a. long range surveillance;
- b. volume surveillance; and
- c. multi-target tracking and targeting.



**Figure 3 - Small CEA-FAR Array**

Each antenna face is made up from a selectable number of tiles with typically 40 to 80 in use for long-range surveillance applications. An Array Interface assembly comprising IF signal combiners and dividers and distributed power supplies and control provides the integration required for the cooperation between the tiles.

The below decks electronic units, signal and data processing, are packaged in a set of CEA's purpose designed equipment modules. These provide full environmental protection and ease of installation and maintenance. Larger systems typically utilise an independent signal processing set per face of the array, or at least redundant systems. This type of installation provides the dual advantages of very high volume scan rates and graceful degradation, as each signal processing assembly is able to provide time shared operation for one or multiple faces through the optional array interchange assembly.

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1-2

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CEA-FAR Technical OverviewSystem Overview

### 1.3 CEA-FAR SCALABILITY FOR SMALL SHIP INSTALLATION

CEA-FAR has many characteristics that make it well suited to the small ship (down to 500 tonnes) surface surveillance role. It has a low radar active and passive radar signature. The IR signature is also low due to the high efficiency of the array which typically requires less than 5 kW from the ship's power supply. No cooling or waveguide systems are required. Due to its low weight (all up less than 2 tonnes for 6 faces), structural requirements are minimised – even for modifications to in-service vessels. In addition, its modular electronic systems allow installation in confined spaces.

The radar is electronically stabilised for pitch, roll, heading and ship's speed.

By employing 6 faces instead of the usual 4, beam-patterns are improved over the entire hemisphere. The degradation from 0° to 30° is minimal compared to the degradation from 0° to 45° for conventional four faced arrays. Six faces also allow two adjacent faces to provide overlapping emergency coverage should a face sustain significant damage.

The Elevation Scan range is greater than 60 degrees.

The system is designed for very high availability by allowing soft failure through multi-step graceful degradation and redundancy.

### 1.4 OPERATIONAL FLEXIBILITY

CEA-FAR's operational flexibility is demonstrated by its numerous operational modes, examples of which are listed below:

- a. long-range mode  $\geq 200$  km,
- b. short-range, high-resolution, high angle mode,
- c. horizon scan modes,
- d. medium-range modes, and
- e. LPI modes.

### 1.5 MULTI-ROLE FEATURES

CEA-FAR also possesses the following multi-role capabilities, which can also be configured dynamically:

- a. surveillance (volume and horizontal search);
- b. targeting and Fire Control;
- c. Surface, Air, Helo, ASMD;
- d. ECCM; and
- e. navigation.

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1-3

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CEA-FAR Technical Overview

System Overview

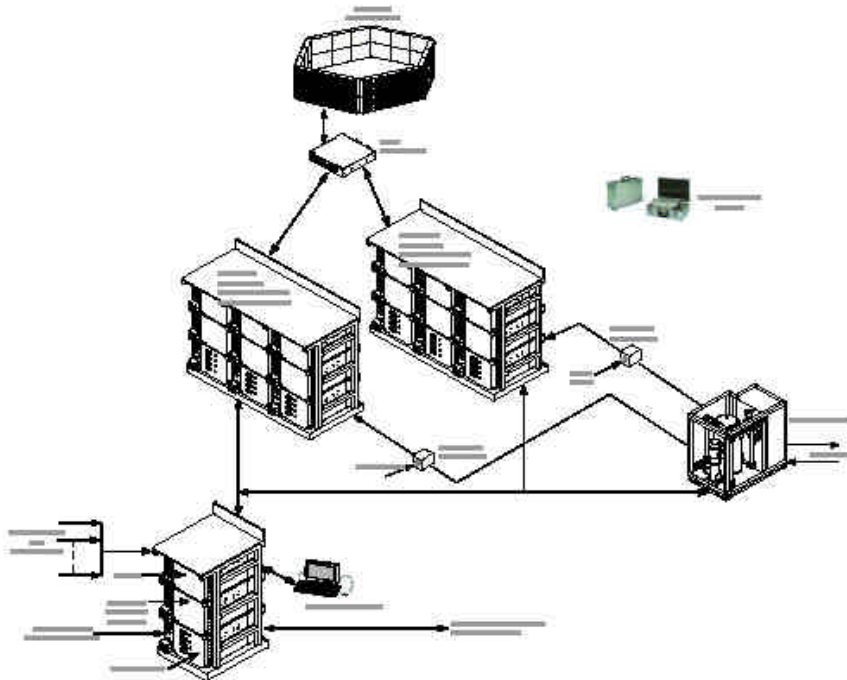


Figure 4 - System Integration – Full Capability System

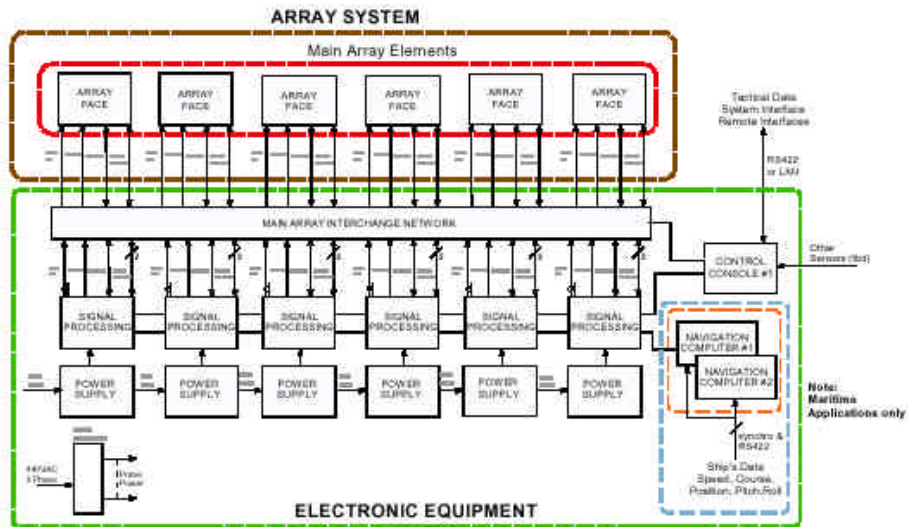


Figure 5 - System Block Diagram – Full Capability System

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1-4

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CEA-FAR Technical Overview

Technology Description

## 2. TECHNOLOGY DESCRIPTION

The CEA-FAR system uses high reliability GaAs MMIC's and highly integrated digital signal processing technology to achieve its economic and reliable performance. These enabling technologies include integrated GaAs phase shift and microwave devices, large array programmable logic and 1600 Million Instructions Per Second DSPs. These device technologies, combined with a unique architecture and innovative antenna element format, provide a cost effective and high performance solution. The major sub-systems of the CEA-FAR technology base are individually discussed below.

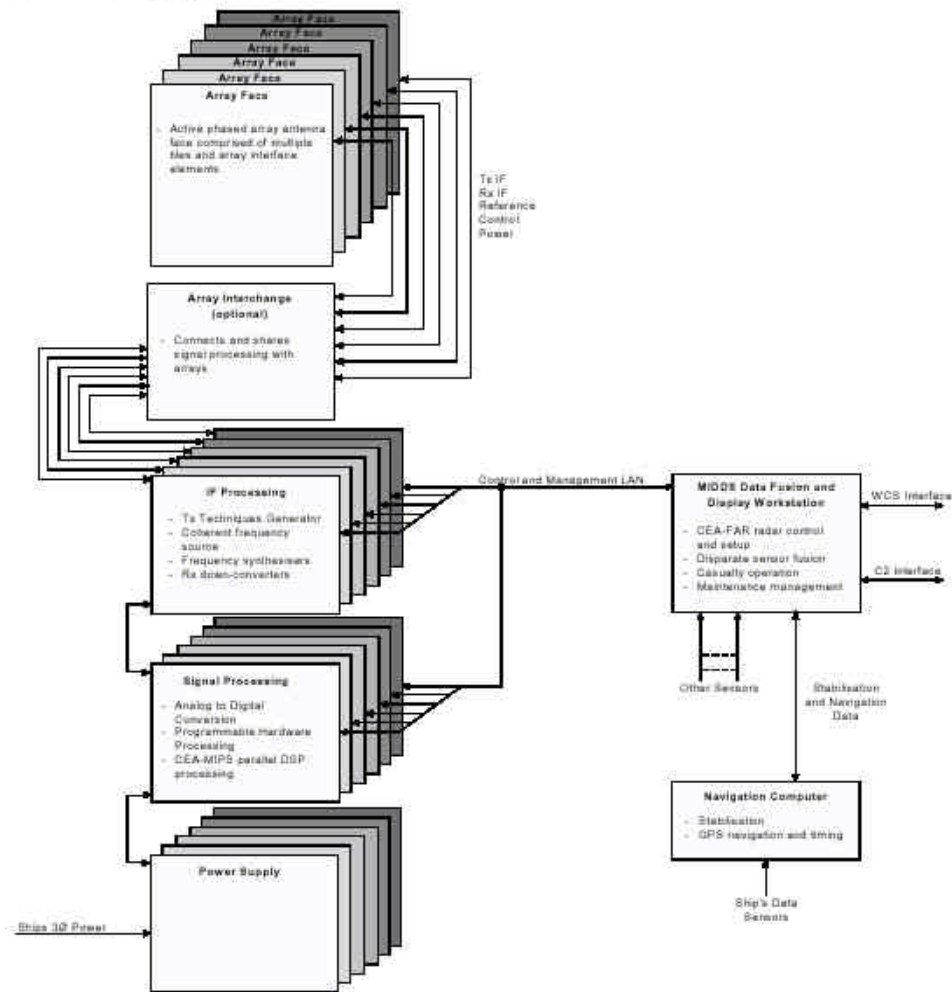


Figure 6 - CEA-FAR MFR

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CEA-FAR Technical Overview

Technology Description

## 2.1 ANTENNA SYSTEM

CEA's unique phased array architecture and antenna design provides the basis for phased array programs in L, S and X-Band frequencies.

The antenna lowest replaceable unit provides 64 wideband (>400 MHz) elements in each tile. Each element has its own accurate and high resolution GaAs phase shifter and control electronics to ensure absolute control over both transmit and receive beam-patterns and pointing accuracy. Conversion to and from the wideband UHF transmit and receive IF system is performed in the tile, which ensures easy connectivity with coaxial cable between tiles, array faces and the signal processing system. Beam steering times are typically less than a few microseconds.

A series of array interface modules are provided as part of the array structure. These small passive IF divider and combiner modules are used to distribute and collect transmit and receive signals across an array face.

The configuration and beam forming required by an antenna system is supported by a full range of software design and development tools. These PC hosted programs allow the modelling and assessment of antenna system impact on system performance and the optimisation of antenna beam-patterns for the operational functions allocated to the radar system.

## 2.2 TECHNIQUES GENERATOR

The transmit waveform techniques generator is a multi-channel wideband waveform generator comprised of a stable master reference oscillator system and complementary on-line programmable 100 MHz bandwidth vector modulation system. This provides complex intra and inter-pulse modulation capability with timing control down to nanoseconds. The technique generator can operate in a single channel mode or provide simultaneous parallel channels. The technique generator operates with a large number of waveform timing and modulation options to provide pulse-to-pulse and burst-to-burst agility and functional optimisation. These programmable waveforms are generated and supported in an offline PC hosted environment that also provides the tools to download and initialise the system.

The flexibility of the waveform generation system includes simultaneous generation of complex multi-frequency wide bandwidth waveforms which can share array transmit functions.

## 2.3 RECEIVER

The multi-channel receiver can be configured in blocks with multiple simultaneous phase matched and amplitude-balanced channels per block. These channels have simultaneous individual frequency allocation anywhere over the operating frequency range and can be dynamically allocated to functions such as operation with individual technique generator channels or for multi-beam operations such as monopulse or data links. Each receiver is dynamically programmable for bandwidth to match the requirements of the waveform generation or received signal characteristics. Receiver channels can be operated in direct conversion to balanced quadrature baseband signals or used in IF sampling modes where final baseband

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conversion is performed in the digital signal processing. Dynamic balancing is used within the down-conversion process to ensure optimised dynamic range and I/Q balance.

## 2.4 HARDWARE SIGNAL PROCESSOR

The CEA Hardware Processor environment provides multiple channels of balanced I and Q signal conversion at a continuous 160 Mega-sample/sec. This process allows the dynamic filtering and demodulation of received signals in the digital domain. Effective dynamic ranges of more than 14 bits are achievable on most surveillance waveform types. The signal processing which follows is a continuous 36-bit resolution and allows for parallel operation of multiple channels. The signal processing algorithms embedded in the programmable logic of the Hardware Processor provide full throughput rates for signal processing of all sampled signals from multiple parallel receiver channels. The specific algorithms used to process waveforms in multi-function applications can be dynamically selected on a pulse burst to pulse burst basis.

## 2.5 CEA-MIPS MULTI-PROCESSOR ENVIRONMENT

The CEA-MIPS multi-processor environment provides a multi-channel capability for signal processing using the latest TEXAS Instruments DSPs in a unique data-sharing environment that provides up to 25.6 GIPS of processing power. This environment is scalable to meet application specific requirements and future expansion needs. Additional processor modules can be added to a basic configuration without hardware changes to bring the system up to its full potential capability.

## 2.6 SOFTWARE

An existing base of more than 200,000 lines of radar code is operating in the CEA-FAR radar baseline. An additional 130,000 lines of code exist in the associated multi-sensor data fusion product (MIDDs) which provides the standard maintenance/casualty and integration system for CEA-FAR and other surveillance products.

### 2.6.1 Operational Firmware and Programmable Logic

Extensive and proven software facilities exist for the functions of beam management, waveform processing and automatic detection and tracking. Additionally, video extraction for display purposes and extensive communications and control processing are provided.

### 2.6.2 Support Software

PC-based software is available to support the management and development of application specific algorithms and processes. This software includes:

- a. high level operational front end,
- b. waveform design and simulation,
- c. system performance modelling,
- d. beam-forming and beam management tools, and
- e. task scheduling tools.

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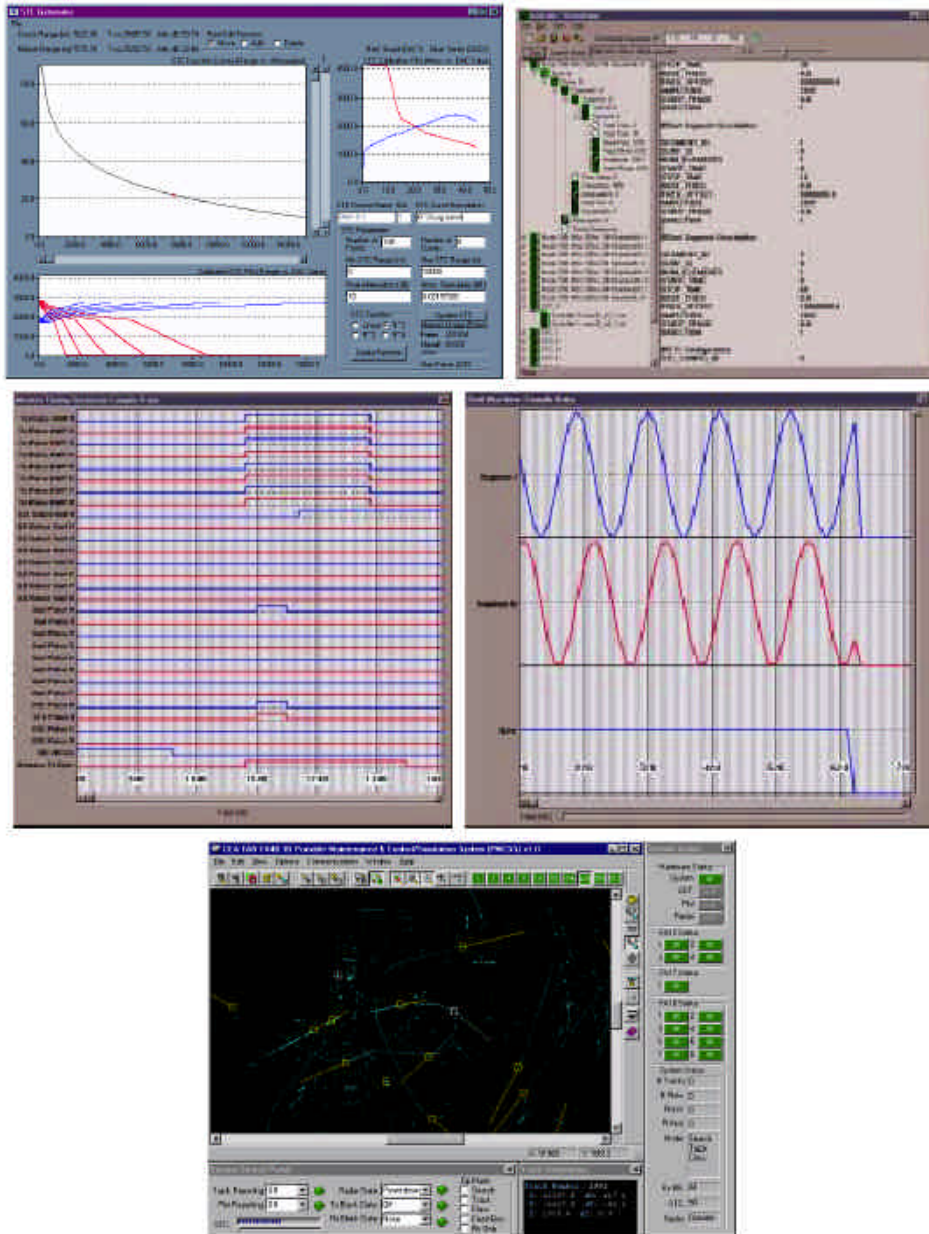


Figure 7 - Support Software

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### 2.6.3 Source Code and Supporting Design Data

CEA recognises the requirement of customers to manage their destiny in relation to mission critical systems. It is in this environment that we are willing to discuss and implement appropriate data release and support processes to ensure through life supportability so long as the protection of intellectual property rights and potential is assured.

CEA also recognises that customers may wish to provide application specific algorithms and waveforms that give the radar specific capability or personality. A full range of support software tools can be provided which allow simulation, modelling and uploading of new waveforms, programmable logic, DSP and embedded control processor application modules.



## Appendix D: AN/SPY-1A Technical Details

This discussion provides some of the engineering details for the AN/SPY-1A radar, which is a major element of the AEGIS weapons system. The AN/SPY-1A was designed in 1970, first operated at a land-based test site in 1973, with subsequent deployment on the *USS Norton Sound*. This Appendix draws upon descriptions and specifications of the AN/SPY-1A that can be found in the unclassified engineering literature.<sup>9,10,11,12</sup>

The basic design of the antenna was intended to support active and passive search, to include monopulse angle tracking of friendly targets, hostile targets and interceptor missile communications links. The stressing environmental conditions in which this radar operates require survival and operation under icing conditions where the wind speed is 80 miles per hour with an ambient temperature range of - 20 F° to + 120 F° at humidities up to 100%. It was designed to survive nuclear blast limits and intense vibration up to 25 Hz. Its degree of reliability was designed to accommodate 4 year intervals between major repairs. The array structure (including all equipment) weighs about 17,000 lbs.

Figure F-1 shows a general schematic of the AN/SPY-1A sub-array. The receive sub-arrays are arranged in 10 columns, and each sub-array is connected to a column beamformer. Transmitting and receiving functions are performed by sub-arrays of various sizes, and the receiving function has a somewhat greater number of elements since monopulse pattern characteristics and peak sidelobe control are important in this system (these additional elements are labeled 'REC ONLY' in the schematic).

Each of the array consists of 4480 phase shifters and 1120 quad drivers. These are arranged in 140 modules, with each module having 32 elements. A receiver sub-array is composed of two modules (*i.e.*, 64 elements), and a transmitter sub-array is composed of two receiver sub-arrays (*i.e.*, 128 elements).

Figure F-2 shows the AN/SPY-1A on board a Ticonderoga-class ship and as a modified unit appears at NSSL.

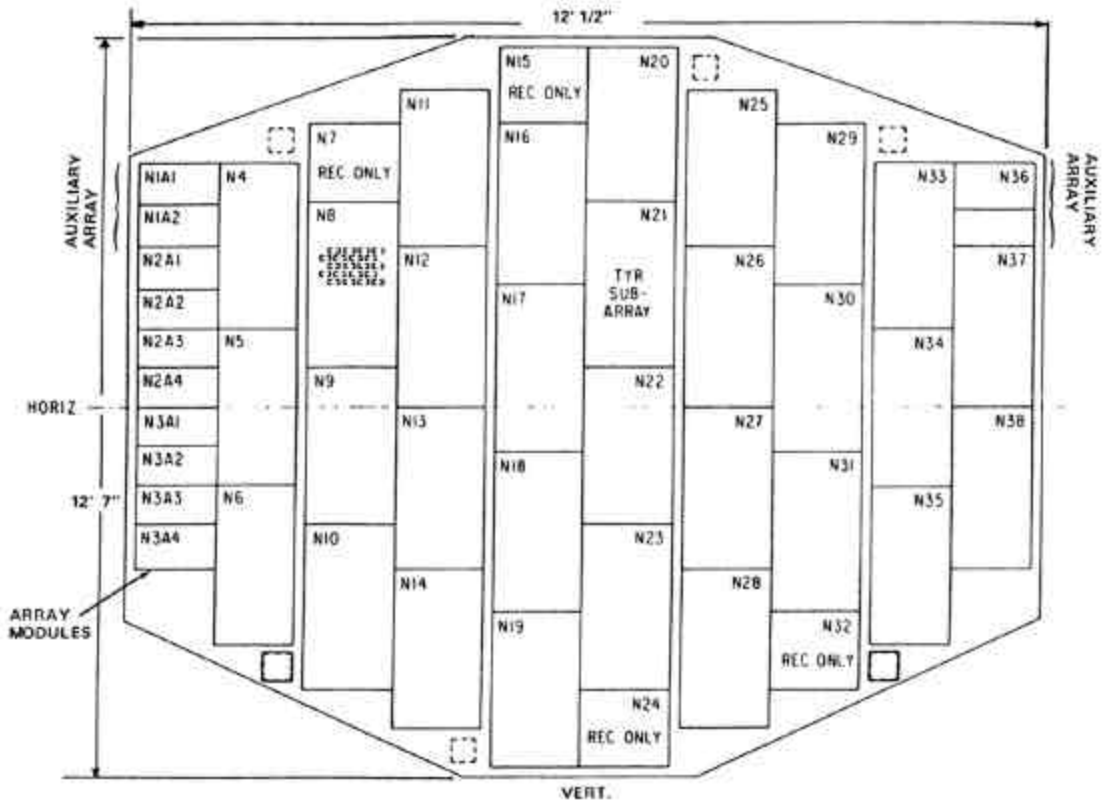


Figure F-1. Rear view of the AN/SPY-1A array layout.<sup>10,11</sup>



Figure F-2. AN/SPY-1A onboard the *Ticonderoga* and during installation at the NSSL.

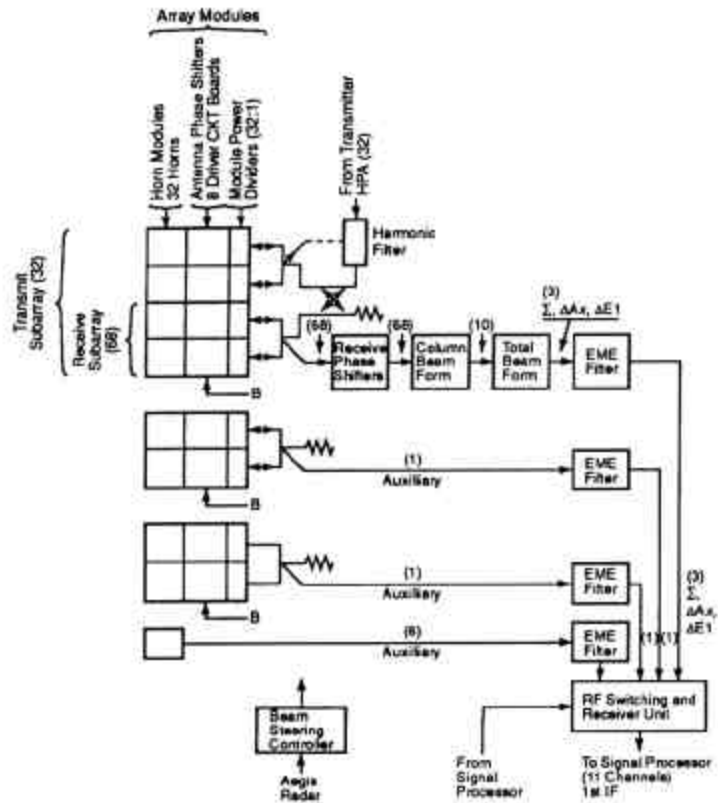


Figure F-3. Functional diagram for the AN SPY-1A array.<sup>12</sup>

The degree of component reliability actually achieved for the AN/SPY-1A is known from four years of field experience in the late 1970s. The limiting components are the phase shifters and drivers, as indicated in the data in Table F-1.

Table F-1. AN/SPY-1A Array Reliability (1974-1977)<sup>11</sup>

Component	Device Hours	Total Events	Event Rate / 10 <sup>6</sup> hours	Allocation / 10 <sup>6</sup> hours
Phase Shifter	132,106,240	7	0.0529	5
Phase Shifter Driver	33,026,560	238	7.2	25



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## 9. References

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- <sup>6</sup> R.A Brown, V.T. Wood, D. Sirmans, "Improved Tornado Detection Using Simulated and Actual WSR-88D Data with Enhanced Resolution," *Journal of Atmospheric and Oceanic Technology* Vol. 19, No. 11, 1759-1771 (2002).
- <sup>7</sup> NWS OS&T data (private communication, Dr. Daniel Melendez).
- <sup>8</sup> *Weather Radar Technology. Beyond NEXRAD*, National Academy of Sciences Press, Washington, D.C. (2003).
- <sup>9</sup> *Jane's Radar and Electronic Warfare Systems (2004 Edition)*, Naval / Coastal Surveillance and Navigation Radars, Article # 1364.
- <sup>10</sup> R.M. Scudder and W.H. Sheppard, "AN/SPY-1 Phased Array Antenna," *Microwave Journal*, pp. 51-55 (May 1974).
- <sup>11</sup> W.T. Patton, "Microwave Design for Reliability-Availability – The AN/SPY-1 Radar System," *Military Microwave Conf. Proc.*, London, pp. 177-192 (Oct. 1978).
- <sup>12</sup> *Practical Phased-Array Antenna Systems*, (Eli Brookner, Ed.), "Compact, Constrained Feed Phased Array for AN/SPY-1", section 8. Artech House, Boston (1991).