A History of Terrain-Following Radar

By

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DISCLAIMER

The opinions expressed in this report are strictly those of the author and are not necessarily those of Raytheon Company, Texas Tech University, nor any U.S. Government agency.

ABSTRACT

This paper will explore the past, present and possible future of a sub class of radar systems known as Terrain-Following Radar (TFR). This class of radar is used by aircraft to allow them to fly close to the surface to avoid detection by groups that would be interested in knowing about the approach of an aircraft. This will focus primarily on U.S. military systems, but will not cover any classified issues. The coverage will be the history of various TFR systems that have been developed over the years. The present will cover the current state of TFR radar systems, including known fielded systems. The future will speculate on possible growth areas for TFR systems.

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CHAPTER I
INTRODUCTION

Terrain-following radar systems (TFRs) are a class of airborne radar which is used for low and very low level flight by looking at the terrain ahead of the aircraft and providing guidance to the pilot and/or the aircraft flight control systems to keep the aircraft at a specified altitude above the ground. In this application, the altitude is generally 500 feet or lower at speeds in excess of 600 knots. The general use for this type of system is covert penetration of an opponent's airspace, coming in below the normal air surveillance radar systems. These systems have been in existence for more than 50 years and have made covert airborne operations much safer for military pilots and crew members.

Mission success for these aircraft employing terrain-following radars is measured in two basic ways:

- The aircraft successfully completes its mission while avoiding detection by unfriendly forces
- The aircraft successfully completes its mission while avoiding terrain obstacles.

The basic premise of terrain-following radars is fairly simple – an aircraft flies low enough to be below aircraft detection radar systems, yet maintains a safe enough altitude to avoid any objects on the ground. However, the technology behind terrain-following radars is very complex. The latest terrain-following radar system runs 63 computations every 50 milliseconds in the delicate balancing act of keeping an aircraft below detection levels and from slamming into the ground.

The major supplier of these systems over the years has been Raytheon and the companies it has acquired over the years such as Texas Instruments Defense Electronic Systems and Hughes.

At Raytheon, the motto is "Customer Success is Our Mission" with a focus on "Mission Assurance." Raytheon wants its customers to never, ever have a doubt when they see the Raytheon name on anything. Whether the user of Raytheon systems and services is a soldier, sailor, airman or Marine, customers depend upon Raytheon to do the job right.

The mission of terrain-following radars is to keep military pilots and onboard crew members alive so they can come home safely to their families. It's a mission Raytheon takes very seriously, as it should – when systems are guiding aircraft at 100 feet above the ground at speeds up to 600 knots. System failure is not an option.

This thesis will give the reader an overview of how terrain-following radar technology works, illustrate how the terrain-following system integrates with other systems on the aircraft, and give a history of the radar systems, their technology upgrades, and the platforms on which they've been used.

CHAPTER II
WHAT IS RADAR

2.1 A Brief History

To start to understand what a terrain-following radar is, a basic explanation of what a radar is will be required. Radar is an acronym for "radio detection and ranging." It is a system of components, which use electromagnetic waves for detection, and location of objects. The radar system generates and transmits a predefined waveform, detects the received echo, and displays the echo (target) on a display [Skolnik, 1988]. Heinrich Hertz, in 1886, tested the theories of Maxwell and demonstrated the similarity between radio and light waves. Hertz showed that metallic and dielectric bodies could reflect radio waves. In 1903, a German scientist experimented with the detection of radio waves reflected from ships. The Germans demonstrated the reflected waves, but were unable to operate at long distances. In 1922, Marconi told an audience during a speech that it is possible to design an apparatus that would transmit radio waves at a ship and receive the reflected radio waves, which would then reveal the presence of another ship with its range and bearing attributes. Even though the exact date that radar was developed is not known (probably started near the turn of the 20^{th} century), many use 1935 as the starting date of radar development since many papers, demonstrations, and serious developments began at that time. In the 1930s, several countries presented papers and demonstrated their radar systems and capabilities simultaneously.

By the end of 1934, three engineers from the Naval Research Laboratory in Washington, D.C., detected an aircraft using a 60 MHz pulsed radar. The following year, in Great Britain, an engineer was able to detect an aircraft using bi-static radar. That same year, the French were testing radars with different wavelengths (radar frequencies). Also the same year, the Germans demonstrated a 600 MHz radar on a naval ship. Concurrently, the Italians began testing radar to detect people and vehicles. The same year, the Russians began detecting aircraft at various distances with different power levels and antenna types. The following year, 1936, the Japanese proposed and demonstrated the Doppler radar principle [Skolnik, 1988].

2.2 A Basic Radar System

Radio waves and light emit a flow of electromagnetic energy. Light waves have higher frequencies while radio waves have longer wavelengths or shorter frequencies. Shorter frequencies allow radio waves to penetrate the earth's atmosphere without degradation. [Stimson, 1983]. By detecting the reflected waves (echo), it is possible to identify objects at night, through haze, smog, fog, or clouds. A basic system, shown in Figure 1, consists of a transmitter to generate the signal, a transmit/receive antenna, a receiver to gather the reflected signals, a synchronizer to keep the system time, and a display device. This type of system requires a device known as a duplexer and possibly other receiver protection devices. This is because the power level of the transmit signal is much larger than the receive signal, and if the transmitter pulse was applied to the receiver it would damage it. Given that the Pulse Repetition Frequency (PRF) of most modern systems is less than 1 millisecond, a mechanical switch is not usable in this system. [Stimson, 1998]

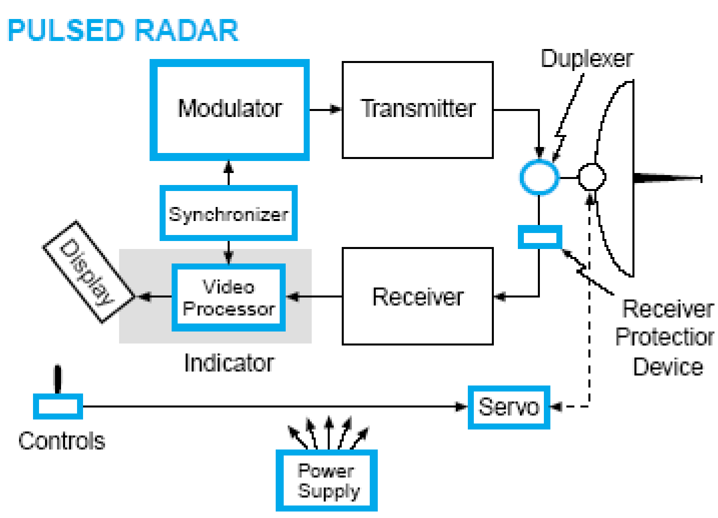

Figure 1. Basic Radar System [Stimson, 1998]

2.2.1 Synchronizer

This unit synchronizes the operation of the various subcomponents, primarily the transmitter, the signal processor and the indicator by generating a continuous stream of very short, evenly spaced pulses. They designate the times at which successive radar pulses are to be transmitted and are supplied to the modulator and indicator.

2.2.2 Modulator

For transmitters that require a high voltage pulse to fire, the modulator generates the high voltage pulse upon receipt of each timing pulse. Frequently the master time trigger comes from the modulator to indicate the time when the transmitter actually fires.

2.2.3 Transmitter

This is a high-power oscillator, frequently a magnetron. For the duration of the input pulse from the modulator, the magnetron generates a high-power radio-frequency wave—in effect converting the dc pulse to a pulse of radio-frequency energy. The wavelength of the energy is typically around 3 cm. The exact value may either be fixed by the design of the magnetron or tunable over a range of about 10% by the operator. The wave is radiated into a metal pipe called a waveguide, which conveys it to the duplexer.

The two more common RF sources used in the transmitter are the cavity magnetron and the traveling wave tube (TWT). The magnetron was invented in Britain in 1940 during World War II, by Randall and Boot. [IEEE Virtual Museum] This type of device produced microwaves with no external signal source other than a high voltage pulse. The method of generating the RF signal is somewhat similar to that of air blowing over the top of a bottle, producing resonance. In the cavity magnetron, Figure 2, the air is an electron stream moving over a number of cavities to produce the microwave signal. The frequency of the signal is determined by the size of the cavities. Tuning of the signal is accomplished by mechanically changing the size of the cavities. These types of devices are relatively small and compact, and produce large amounts of power.

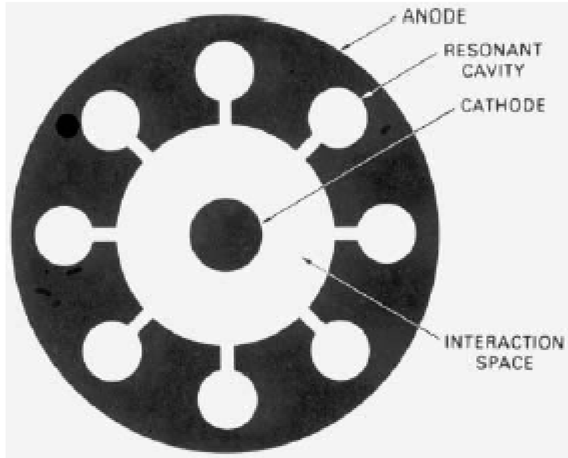

Figure 2. Cavity Magnetron Cross Section [Stimson, 1998]

The other common RF source used in TFR type systems is the traveling wave tube or TWT, Figure 3. This type of device is a power amplifier and requires another high frequency oscillator for the RF signal. The gridded traveling wave tube amplifier, or GTWT, is one of the key developments of the 1960s that made possible the truly versatile multimode airborne radar. With it, for the first time, both the width and repetition frequency of a radar's high-power transmitted pulses could not only be controlled precisely, but be readily changed almost instantaneously to virtually any values within the power handling capacity of the tube. Added to these capabilities were those of the basic TWT: the high degree of coherence required for doppler operation; versatile, precise control of radio frequency; and the ability to conveniently code the pulse's radio frequency or phase for pulse compression. [Stimson, 1998]

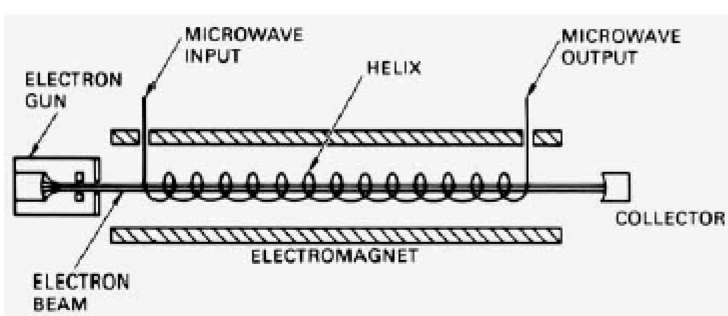

Figure 3. Traveling Wave Tube [Stimson, 1998]

2.2.4 Duplexer

This is essentially a waveguide switch. Like a “Y” in a railroad track, it connects the transmitter and the receiver to the antenna. Unlike a railroad switch, however, the duplexer is usually a passive device, which needn’t be “thrown.” Sensitive to the direction of flow of the radio waves, it allows the waves coming from the transmitter to pass with negligible attenuation to the antenna, while blocking their flow to the receiver. Similarly, the duplexer allows the waves coming from the antenna to pass with negligible attenuation to the receiver, while blocking their way to the transmitter.

2.2.5 Antennas

There are a number of antenna schemes which can be used on a radar system. Among the things that must be considered for an airborne radar system are mechanical complexity, reliability, and weight. The more common antenna systems are described here.

2.2.5.1 Parabolic Antenna

In simple radars, the antenna generally consists of a radiator and a parabolically shaped reflector (dish), mounted on a common support (Figure 4). In the most rudimentary form, the radiator is little more than a horn-shaped nozzle on the end of the waveguide coming from the duplexer. The horn directs the radio wave arriving from the transmitter onto the dish, which reflects the wave in the form of a narrow beam. Echoes intercepted by the dish are reflected into the horn and conveyed by the same waveguide back to the duplexer, thence to the receiver. Generally, the antenna is mounted in gimbals, which allow it to be pivoted about both azimuth and elevation axes. In some cases, a third gimbal may be provided to isolate the antenna from the roll of the aircraft. Transducers on the gimbals provide the indicator with signals proportional to the displacement of the antenna about each axis.

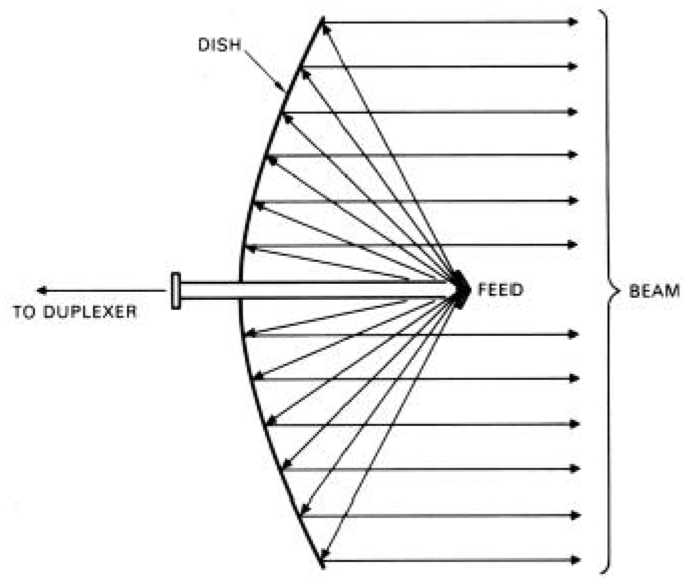

Figure 4. Parabolic Antenna and Feed [Stimson, 1998]

2.2.5.2 Planar Array Antenna

Another type of antenna in common usage is the flat plate or planar array antenna, shown in Figure 5. This type of antenna does not have the usual parabolic shape and feed horn, but instead has a distribution feed from the rear of the antenna and emits through a series of tuned slots on the face plate or front face of the antenna. Some of these type of antennas have additional features to allow direction finding. This type of antenna system still requires a gimbal mount to point it towards the desired location.

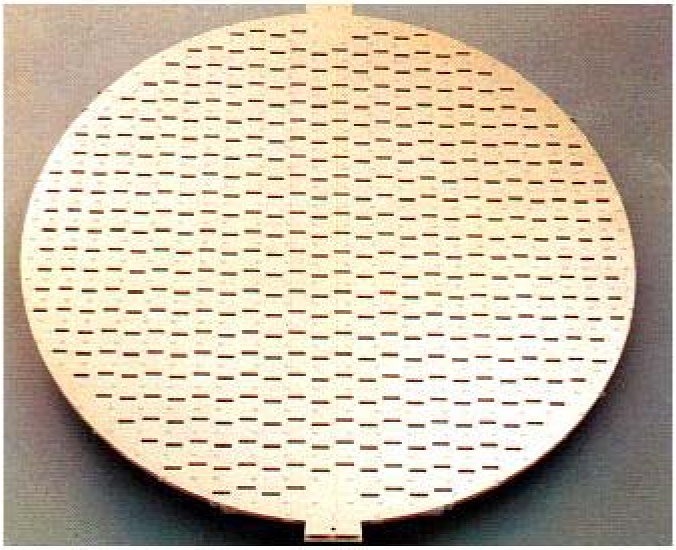

Figure 5. Planar Array Antenna [Stimson, 1998]

2.2.5.3 Phased Array Antenna

The most modern of the antenna types is the phased array. This is a collection of small antenna modules arranged in a grid. This system can be fed from a conventional transmitter in a method similar to that of a planar antenna, as shown in Figure 6.

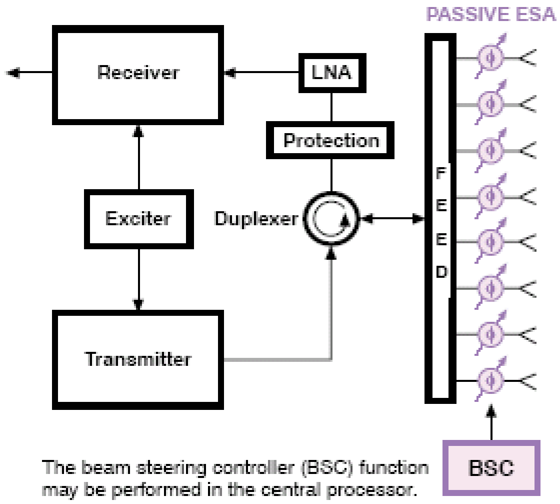

Figure 6. Passive Phased Array [Stimson, 1998]

Alternately, the modules can be transmitter-receiver modules, which will generate the transmit pulse and process the receive data internally, as shown in Figure 7. In both cases, the radar beam is pointed by adjusting the phase of the signal in each module individually. This eliminates the servo control system and mechanical components required to point the antenna in the other antenna systems described.

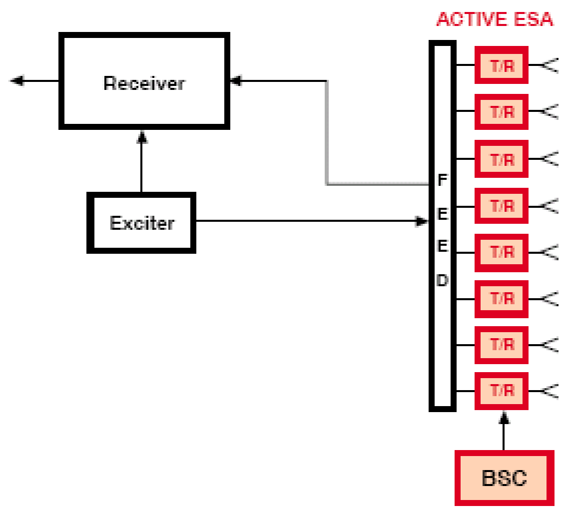

Figure 7. Active Phased Array [Stimson, 1998]

2.2.6 Receiver Protection Device

Because of electrical discontinuities (mismatch of impedances) between the antenna and the waveguide conveying the radio waves to it, some of the energy of the radio waves is reflected from the antenna back to the duplexer. Since the duplexer performs its switching function purely on the basis of direction of flow, there is nothing to prevent this reflected energy from flowing on to the receiver, just as the radar echoes do. The reflected energy amounts to only a very small fraction of the transmitter's output. But because of the transmitter's high power, the reflections are strong enough to damage the receiver. To prevent the reflections from reaching the receiver, as well as to block any of the transmitter's energy that has leaked through the duplexer, a protection device is provided. This device is essentially a high-speed microwave switch, which automatically blocks any radio waves strong enough to damage the receiver. Besides leakage and energy reflected by the antenna, the device also blocks any exceptionally strong signals which may be received from outside the radar—echoes received when the radar is inadvertently fired up in a hangar or is operated while facing a hangar wall at point-blank range, or the direct transmission of another radar that happens to be looking directly into the radar antenna.

2.2.7 Receiver

Typically, the receiver is of a type called a superheterodyne. It translates the received signals to a lower frequency at which they can be filtered and amplified more conveniently. Translation is accomplished by "beating" the received signals against the output of a low-power oscillator (called the local oscillator or LO) in a circuit called a mixer. The frequency of the resulting signal, called the intermediate frequency or IF, equals the difference between the signal's original frequency and the local oscillator frequency.

The output of the mixer is amplified by a tuned circuit (IF amplifier). It filters out any interfering signals, as well as the electrical background noise lying outside the band of frequencies occupied by the received signal. Finally, the amplified signal is applied to a detector, which produces an output voltage corresponding to the peak amplitude (or envelope) of the signal. It is similar to the signal that in a TV varies the intensity of the beam, which paints the images on the picture tube. Consequently, the detector's output is called a video signal. On older simplified radars, this signal is supplied to the indicator. On modern systems, this signal is fed to the signal processor where it is digitized by high-speed analog to digital converters and further processed to gather the desired information from the signal.

2.2.7.1 Analog to Digital Conversion

As mentioned above, analog to digital conversion (ADC) is an important concept in modern radar systems. The entire area of analog to digital conversion is broad enough for an entire paper alone, but a simple converter will be described here. This circuit, shown in Figure 8, is a 3-bit analog to digital converter. In this circuit, the analog input voltage is buffered and sent to the 8 comparators. The comparison voltage for each bit comes from dividing the reference voltage into discrete steps. In this example, assuming the reverence voltage is 0.8 volts, each step will be 0.1 volts, which becomes the step value of the least significant bit. The output of each comparator is then sent to the 8 to 3 bit priority encoder, which will generate a binary number based on the highest active input bit. So this circuit will output a 3 bit number for the input analog voltage. This type of converter will give a total of 8 possible steps for the input voltage encoded into the 3 output bits. Other enhancements can be things like a sample and hold circuit for the input, to freeze a rapidly changing input; output gating to clock all of the bits out together; more stages for more output bits; and memory circuits to hold many readings. The more common type of converters uses a counter and digital to analog converter to provide the reference voltage for the step comparison, which is shown in Figure 9.

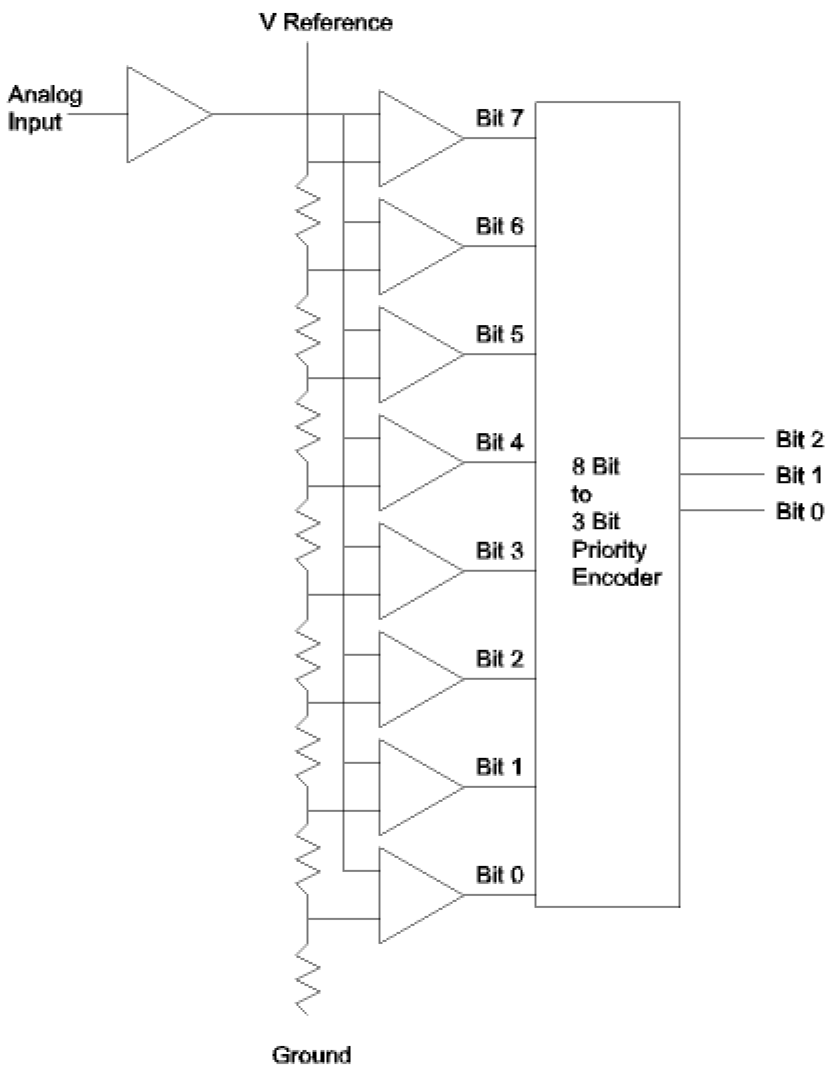

Figure 8. Simple Ladder Analog to Digital Converter

This type of converter has a single comparator, and the reference voltage for the comparison is generated by the digital to analog converter in steps. With this type of converter, the control logic will generate a “start of conversion” and “end of conversion” pulse, and will have a conversion rate related to the clock rate that feeds the circuit.

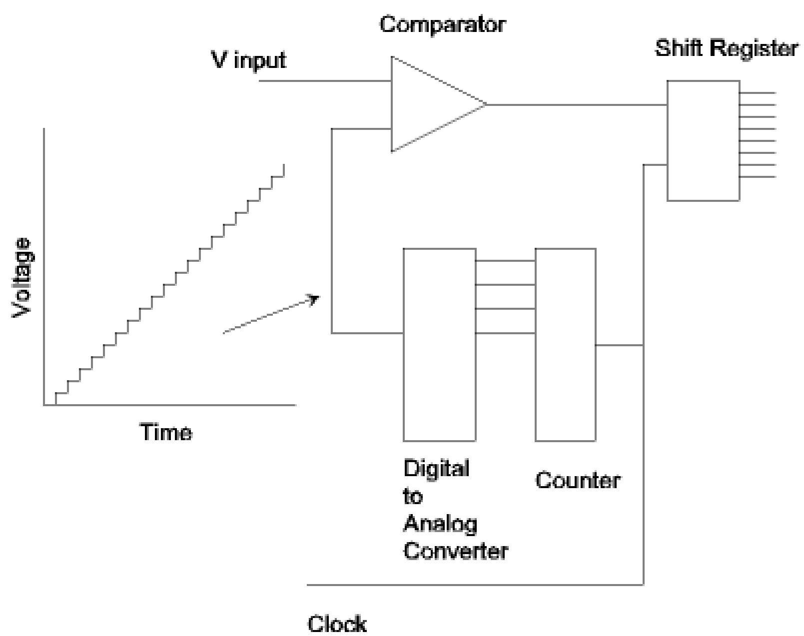

Figure 9. Ramp Type Analog to Digital Converter

2.2.7.2 Digitizing Waveforms

Modern radar systems do not directly display the video data from the receiver on the indicators. The video data from the receiver is passed through an AD converter, similar to what was described in the preceding paragraph. The output of the ADC is clocked into discrete steps and these are stored in the computer memory as a digital representation of the waveform. This process is illustrated in Figure 10. In part A, you have a constant time varying analog video signal, where the amplitude would be the Y axis and time would be the X axis. If one was to break this signal into discrete time steps, as shown in B, you get small windows where the AD conversion takes place. The output of the AD conversion is shown in a plotted form in part C or as the actual values in D. As one may observe, there is some minor loss of detail in the waveform during the conversion process, but the main features are intact. Actual digitizer systems sample and convert with much finer steps than this example, which give more fidelity of the digitized waveform to the original.

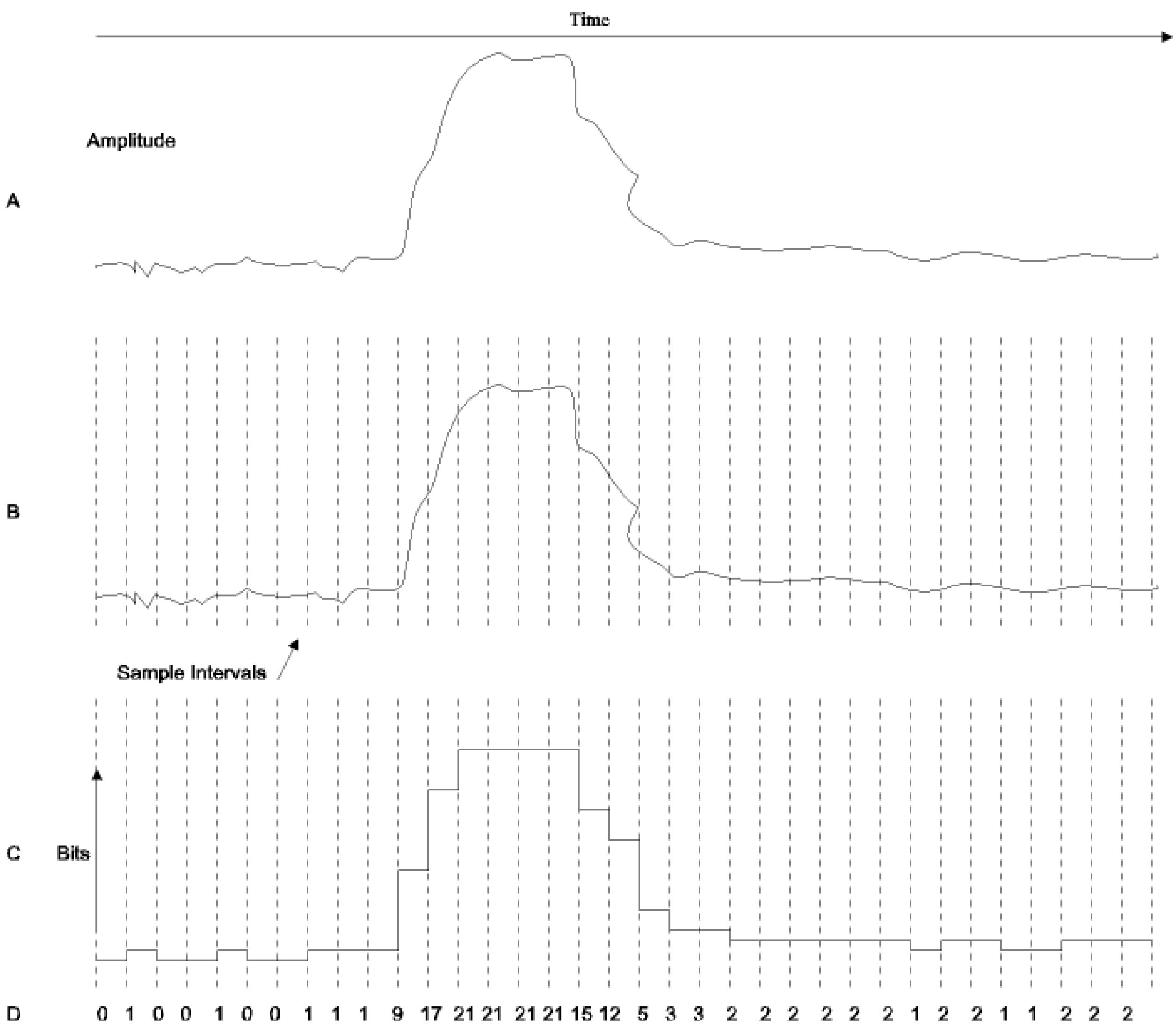

Figure 10. Waveform Digitization Process

2.2.8 Indicator

The indicator contains all of the circuitry needed to display the received echoes in a format that will satisfy the operator’s requirements.

2.2.8.1 The B-Scan Display

This type of display has a rectangular presentation, with the range on the vertical axis and the azimuth on the horizontal axis, as shown in Figure 11. A video amplifier raises the receiver output to a level suitable for controlling the intensity of the display tube's cathode ray beam. The operator generally sets the gain of the amplifier so that noise spikes make the beam barely visible. Target echoes strong enough to be detected above the noise will then produce a bright spot, or "blip." The vertical and horizontal positions of the beam are controlled as follows.

Each timing pulse from the synchronizer triggers the generation of a linearly increasing voltage that causes the beam to trace a vertical path from the bottom of the display to the top. Since the start of each trace is thus synchronized with the transmission of a radar pulse, if a target echo is received, the distance from the start of the trace to the point at which the target blip appears will correspond to the round-trip transit time for the echo, hence to the target's range. For this reason, the trace is called the range trace and the vertical motion of the beam the range sweep. Meanwhile, the azimuth signal from the antenna is used to control the horizontal position of the range trace, and the elevation signal may be used to control the vertical position of a marker on the edge of the display, where an elevation scale is provided. As the antenna executes its search scan, the trace sweeps back and forth across the display in unison with the azimuth scan of the antenna. Each time the antenna beam sweeps across a target, a blip appears on the range trace, providing the operator with a plot of the range versus the azimuth of the target. [Stimson, 1998]

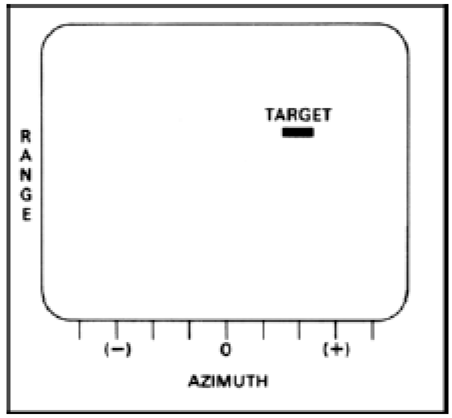

Figure 11. B-Scan Display [Stimson, 1998]

2.2.8.2 PPI Display

The most common type of radar display is the plan position indicator or PPI. This display is either wedge-shaped or circular, depending on the azimuth scan angle capacity of the radar system, Figure 12. On this type of display you get range and bearing to target, and based on the amplitude of the return, an indication of its size. The azimuth movement of the antenna controls the radial sweep axis. The displays either have a chemical or electronic phosphor to make the returns last long enough to see. A bright line indicates the current antenna position and if a target return is detected a bright dot will remain on the display. Frequently this type of display has a number of arced or curved lines called range rings to give an indication of target range.

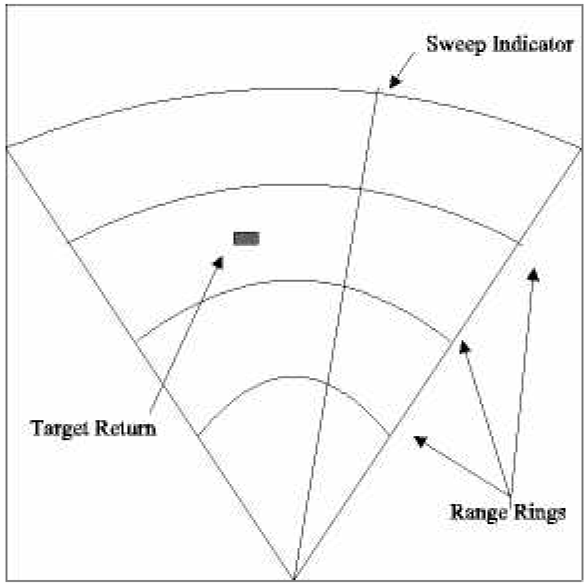

Figure 12. PPI Type Display

2.2.8.3 E-Scan

The E-Scan type of display is a common display for terrain-following systems, as shown in Figure 13. Like the B-Scan, this is a rectangular type of display. The horizontal axis is the range and the vertical axis is the elevation angle. This type of display sometimes uses a logarithmic scale for the horizontal to cover more distance and to expand the near range data. Frequently, other reference lines will be placed on the display to show related information. In the example figure, the radar data would be the band marked “raw video” The zero command line and obstacle warning lines are also shown.

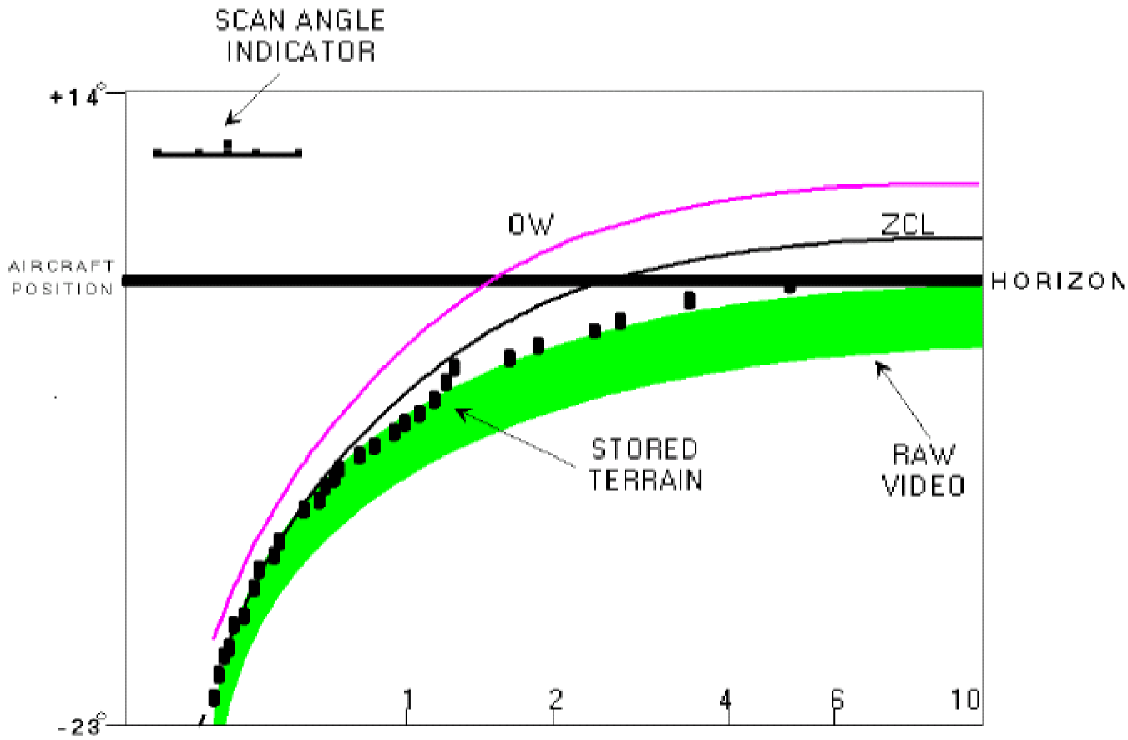

Figure 13. E Squared Radar Display [Woodward, 2005]

2.3 Radar Bands

2.3.1 Band Selection

The selection of the frequency band for a specific application has several factors. These include increased susceptibility to clutter interference, limited detection range and a fall-off in transmitter efficiency at the high end of the spectrum, as opposed to poor angular resolution and large antenna size at the lower end. As a rough guide, current land-based and shipborne air surveillance radars operate across the B- through G-band section of the spectrum (see Table 1 for band definitions); ground-based battlefield surveillance and fire-control radars in the B- through M-bands; naval fire-control and navigation radars in the G- through J-bands (with an emphasis on I-band); airborne surveillance radars in the B- through F-band and airborne fire-control radars in the I/J-band. Some radars will change frequencies on a pulse-by-pulse or batch-of-pulses by batch-of-pulses basis as a counter jamming measure.

2.3.2 Band Designations

Military radar frequencies are described by two concurrent systems of "bands," the first of which has evolved from the system used during the Second World War. During 1969, NATO (the North Atlantic Treaty Organization) adopted a second system, which originated within the Electronic Warfare (EW) community and is still, somewhat confusingly, referred to as the "EW" system within some quarters. Both systems are presented here for completeness [Jane's, 2005].

Table 1. Radar Band Designation [Jane's, 2005]

Historical Radar Bands			**NATO/EW Bands**		
Band Designation	**Frequency**	**Wavelength**	**Band Designation**	**Frequency**	**Wavelengh**
VHF1	0.03-0.3 GHz	1,000-100 cm	**A**	0.03-0.25 GHz	1,000-120 cm
UHF2	0.3-1 GHz	100-30 cm	**B**	0.25-0.5 GHz	120-60 cm
L	1-2 GHz	30-15 cm	**C**	0.5-1 GHz	60-30 cm
S	2-4 GHz	15-7.5 cm	**D**	1-2 GHz	30-15 cm
C	4-8 GHz	7.5-3.75 cm	**E**	2-3 GHz	15-10 cm
X	8-12 GHz	3.75-2.5 cm	**F**	3-4 GHz	10-7.5 cm
Ku	12-18 GHz	2.5-1.6 cm	**G**	4-6 GHz	7.5-5 cm
K	18-27 GHz	1.6-1.1 cm	**H**	6-8 GHz	5-3.75 cm
Ka	27-40 GHz	1.1-0.75 cm	**I**	8-10 GHz	3.75-3 cm
MM3	40-100 GHz	0.75-0.3 cm	**J**	10-20 GHz	3-1.5 cm
			K	20-40 GHz	1.5-0.75 cm
			L	40-60 GHz	0.75-0.5 cm
			M	60-100 GHz	0.5-0.3 cm

Key
1 Very High Frequency 2 Ultra High Frequency 3 Millimeter

2.4 System Timing

The types of radar systems used in a TFR system are pulsed. This system will generate a short high-power pulse to be transmitted. When the transmit pulse is generated, a master trigger starts the timing process. The timing is ended when the receiving antenna detects the return pulse. The delta time between transmit and receive pulses is the range to the target. The RF pulses travel at the speed of light to the target and back, so a round trip time is approximately 2 nanoseconds per foot or 12.3 microseconds per nautical mile (nm). One nm is 6076 feet.

2.4.1 Blind Range

Blind range for a radar system is the distance from immediately in front of the antenna to the distance where detection of returns is possible. There are a number of factors in determining the blind range, but the biggest factor is the recovery time for the duplexer mentioned above. The more power a system has, the longer the recovery time to allow returns to get to the receiver. This range is typically 500-1,500 feet, but varies from system to system. This is important in the design of a terrain-following system, as that is the area immediately in front of the aircraft. The TFR systems need to compensate for this blind range by some method as that is a threat area when flying in adverse conditions (bad weather and/or night).

2.4.2 Maximum Range

The maximum range for a radar system is the time between transmitter fires. For example, if a system has a pulse rate of 2,000 pulses per second, you get 500 microseconds as a pulse interval. With a round-trip time of 2.033 nanoseconds per foot, you get a maximum possible range of 245,900 feet or 46.5 miles. A number of other factors are figured into the maximum range of a given system. Some of these are transmitter power, receiver sensitivity, operating frequency, and atmospheric conditions (rain or high humidity attenuates radar signals in some bands). For most terrain-following radars, the range of interest will be less than 10 miles and more typically three to five miles, depending upon the speed of the aircraft.

Chapter III
Terrain-Following Radar

Bert Bechtel at Texas Instruments invented the terrain-following radar system. The technology was patented in 1959 (US Patent 3568187) and Texas Instruments produced the world's first terrain-following radar system, designated the AN/APQ-101, that same year. As Chapter IV shows, Texas Instruments developed and produced the majority of all of the U.S. military terrain-following systems.

3.1 Goals of a TFR System

The general goals of a TFR system can be listed in two categories. The first of these would be to minimize detection by the opponent. A mission will fail if the aircraft is detected, so this is a significant factor.

Minimize detection by
- Minimizing altitude
- Maximizing terrain masking
- Minimize RF signature
- Avoiding or minimizing time in threat coverage
- Operating at night
- Operating in adverse weather

The other major goal for a TFR system is to maximize flight safety. Eliminating detection is of no value if the aircraft crashes either inbound or outbound on the mission.

Maximize flight safety by
- Maintain safe distance from terrain
- Avoid unexpected obstacles, weather
- Proven system performance
- High user acceptance
- High reliability/availability
- System status indicators

These goals can be visualized by the graph shown in Figure 14.

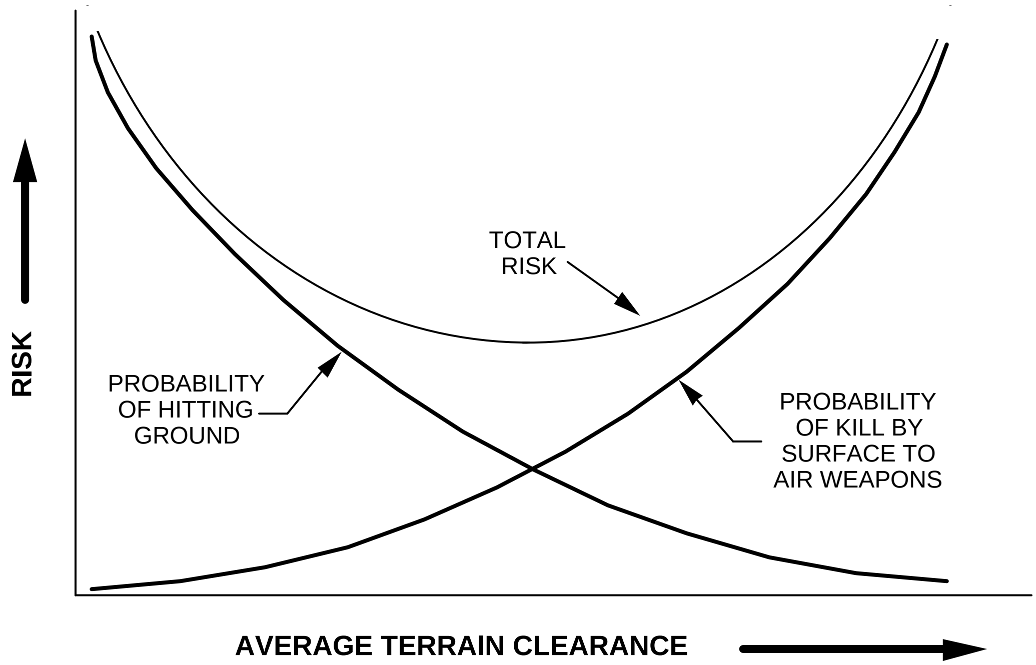

Figure 14. TFR Clearance vs. Risk [Woodard, 2005]

3.2 Covert Penetration

As stated in the introduction, the purpose of a TFR system is to facilitate covert penetration of an opponent's airspace. This is accomplished by maintaining a flight path low to the ground. As shown in Figure 15, the aircraft following the terrain on the low-level flight path is less likely to be detected than the aircraft at the high-level flight path. If the flight path takes into account known or detected radar sites, and the flight path is set accordingly, as shown in Figure 16, the probability of detection is extremely low.

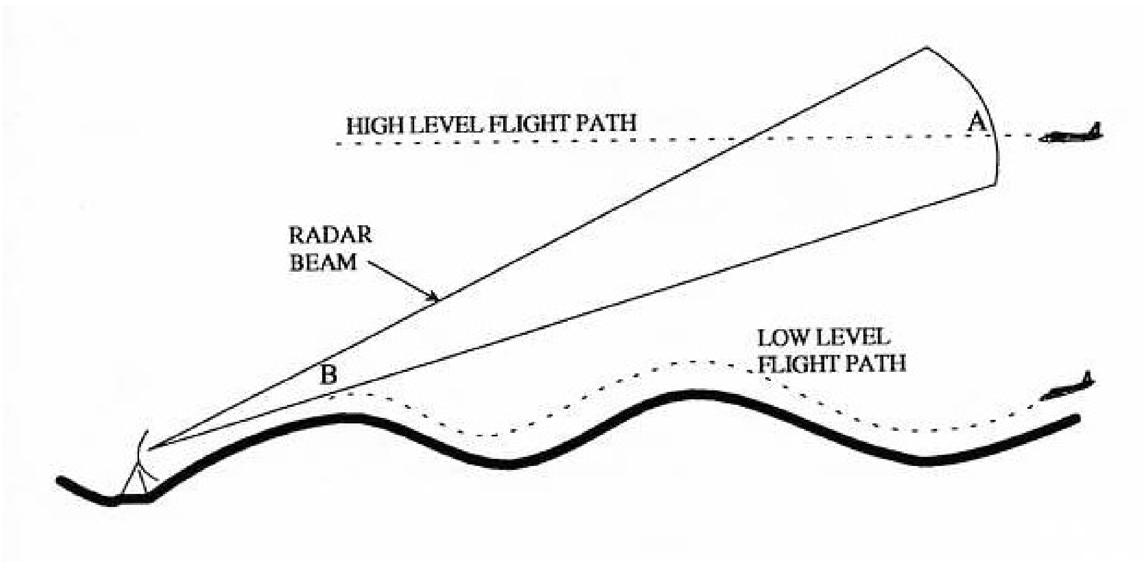

Figure 15. TFR Covert Approach [Ramey, 1994]

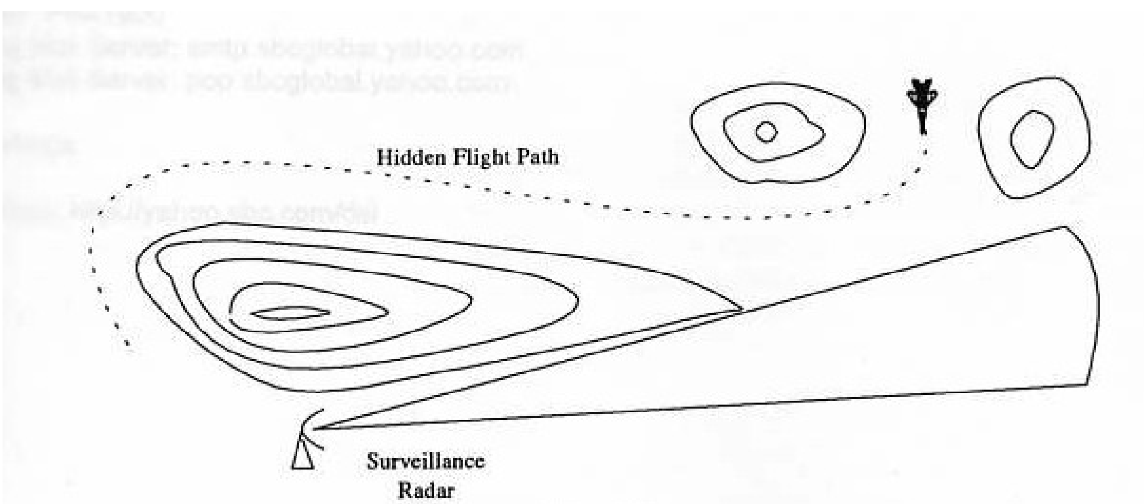

Figure 16. Covert Approach Path [Ramey, 1994]

3.3 TFR Scan

A TFR system will scan the airspace in front of the aircraft with a vertical scan, as shown in Figure 18, forming a wedge of data in both the altitude and azimuth directions. An antenna scan pattern to produce this wedge is shown in Figure 17. In this type of scan, the horizon will be near the middle of the vertical scans, which will produce the wedge to the left, right, above and below the aircraft. All ground returns gathered by this scan are collected and measured.

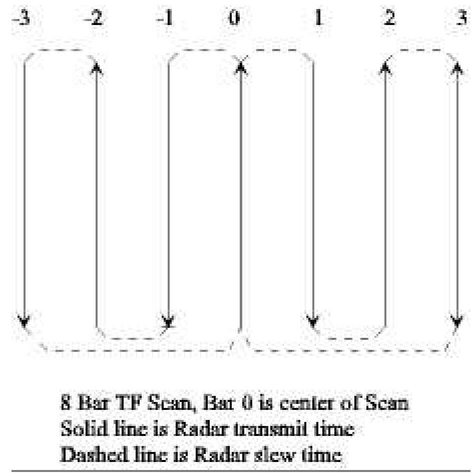

Figure 17. 8 Bar TF Radar Scan

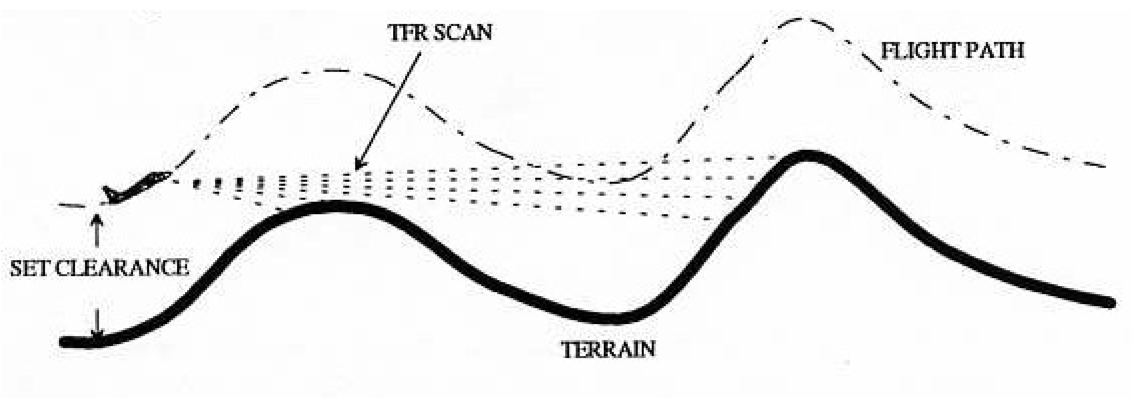

Figure 18. TFR Scan [Ramey, 1994]

3.4 Obstacle Phases

Any obstacles, which would penetrate the flight path of the aircraft, result in a command to the pilot or flight control system to pull up. When the obstacle is cleared, a command to push down is issued to maintain the set clearance altitude. The phases of clearing an obstacle are shown in Figure 19.

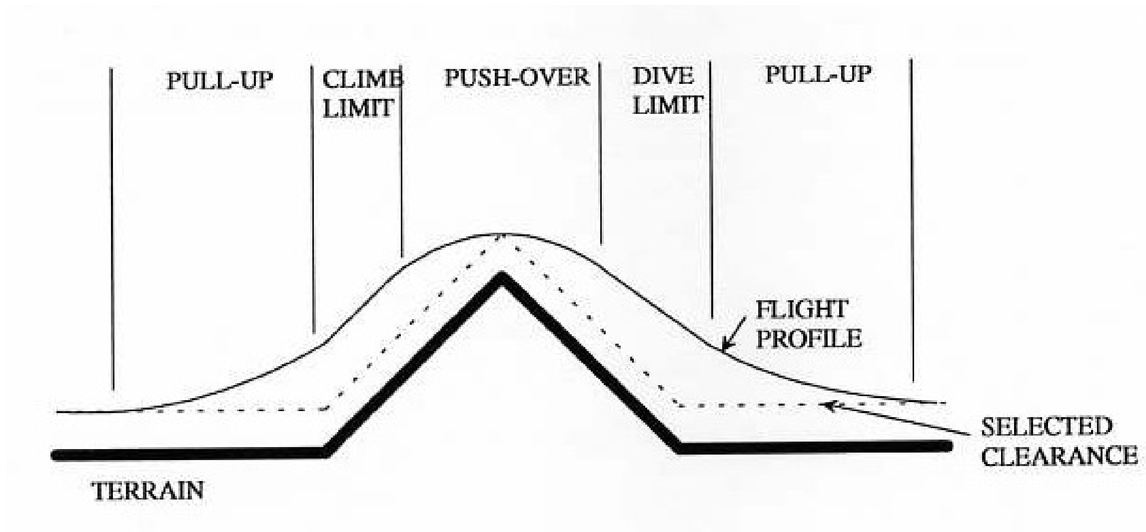

Figure 19. Flight Path Obstacle Phases [Ramey, 1994]

As most of the aircraft are flown by the human pilot and not auto-pilot, the algorithms used to fly over an obstacle have some safety margins built in. If the pilot is late in performing the pull-up maneuver, there will still be some time to clear the terrain, Figure 20. The tradeoff is the set clearance will be exceeded, resulting in an increased risk of detection, Figure 21.

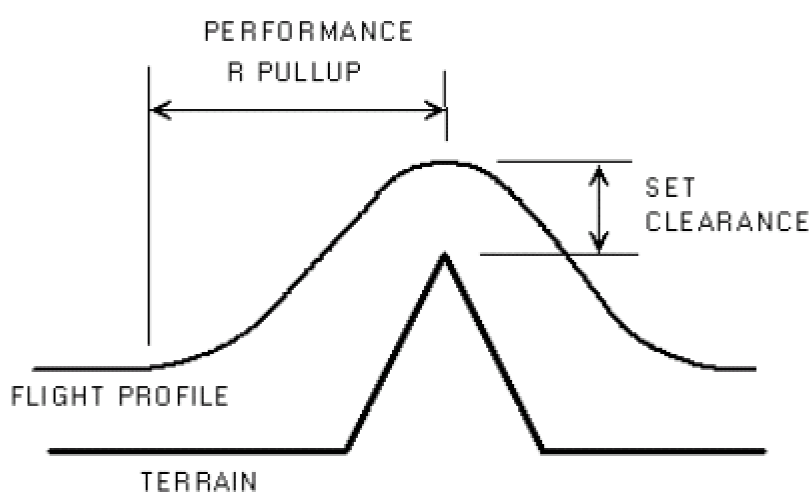

Figure 20. TF Pull-up Performance Safety Margin [Woodward, 2005]

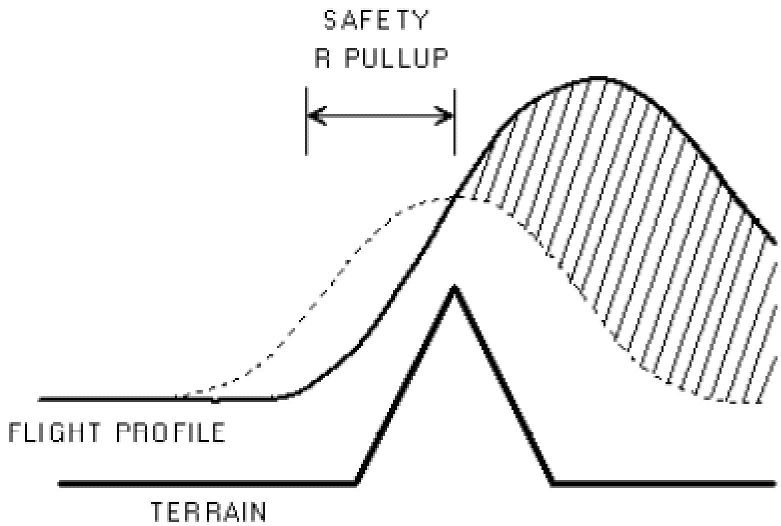

Figure 21. Late Pull-up Effect [Woodward, 2005]

When the aircraft needs to make a turn in flight, the radar will need to look into the direction of the turn to determine obstacles that could penetrate the flight path. Figure 22 shows this possible scenario. In this figure, the OW line is the obstacle warning line. If the terrain penetrates this line, the system will issue a warning to the pilot. The other line is the zero command line (ZCL). When the terrain penetrates this line, the system will start issuing pull up commands. If the aircraft does not look into the path of the turn, the possibility exists for the obstacle to be undetected and result in an unsafe flight path.

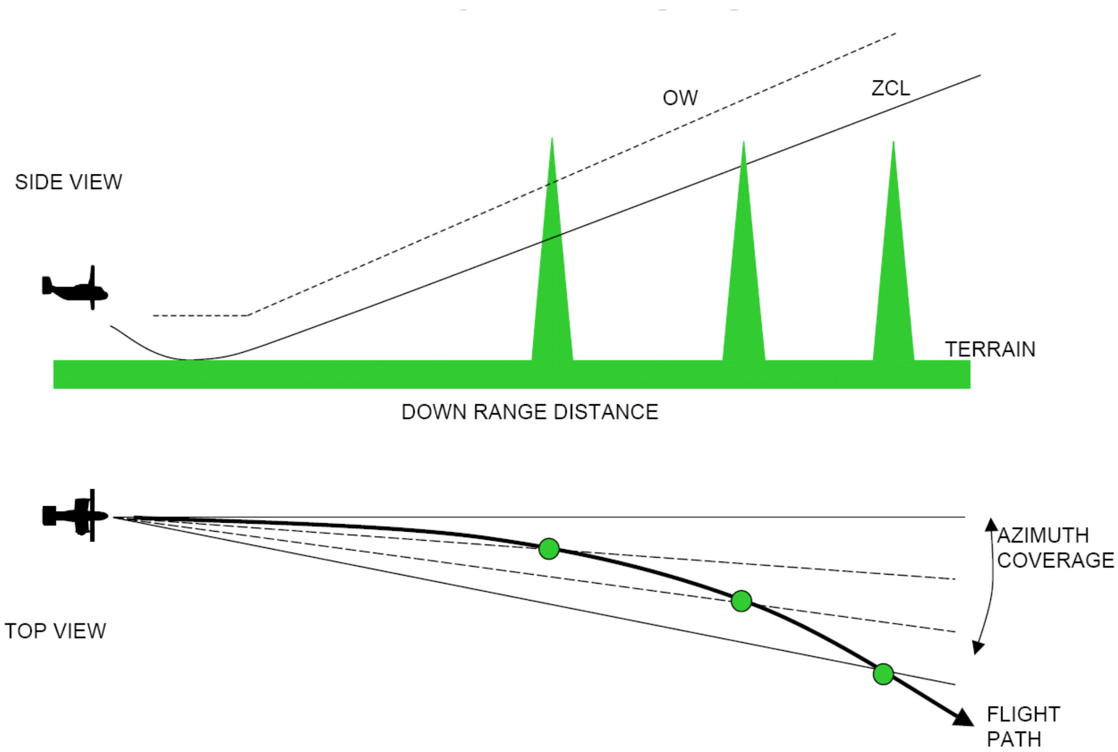

Figure 22. Geometry for Turning Flight [Woodward, 2005]

3.5 TFR Interface to Other Systems

A terrain-following radar forms a closed loop control system between the radar, the aircraft, and in most cases the pilot. In order to generate the commands, a TFR system interfaces with multiple aircraft systems as shown in Figure 23. The TFR computer uses radar return from the terrain and inputs from other sensors such as speed, altitude, pitch, and acceleration to generate these commands. The TFR algorithm compares the current aircraft condition to the desired aircraft condition required to safely maintain a set clearance above the terrain, and generates the appropriate pull-up or push-over command. The set clearances are usually pilot selectable and range from 100 feet to 1,000 feet. [Ramey, 1994] Aircraft information fed to the radar includes, but is not restricted to, attitude (pitch, roll, yaw), speed, altitude above ground, altitude above sea level, ground track, and current climb capibility. As one might conclude, terrain-following radar systems are very dependent upon the current state of the aircraft. The systems are designed for a specific aircraft, based upon the performance characteristics of that aircraft.

The aircraft factors are tuned during flight test to provide optimum performance. A system designed for a C130 aircraft would perform poorly in an F16, and vice versa.

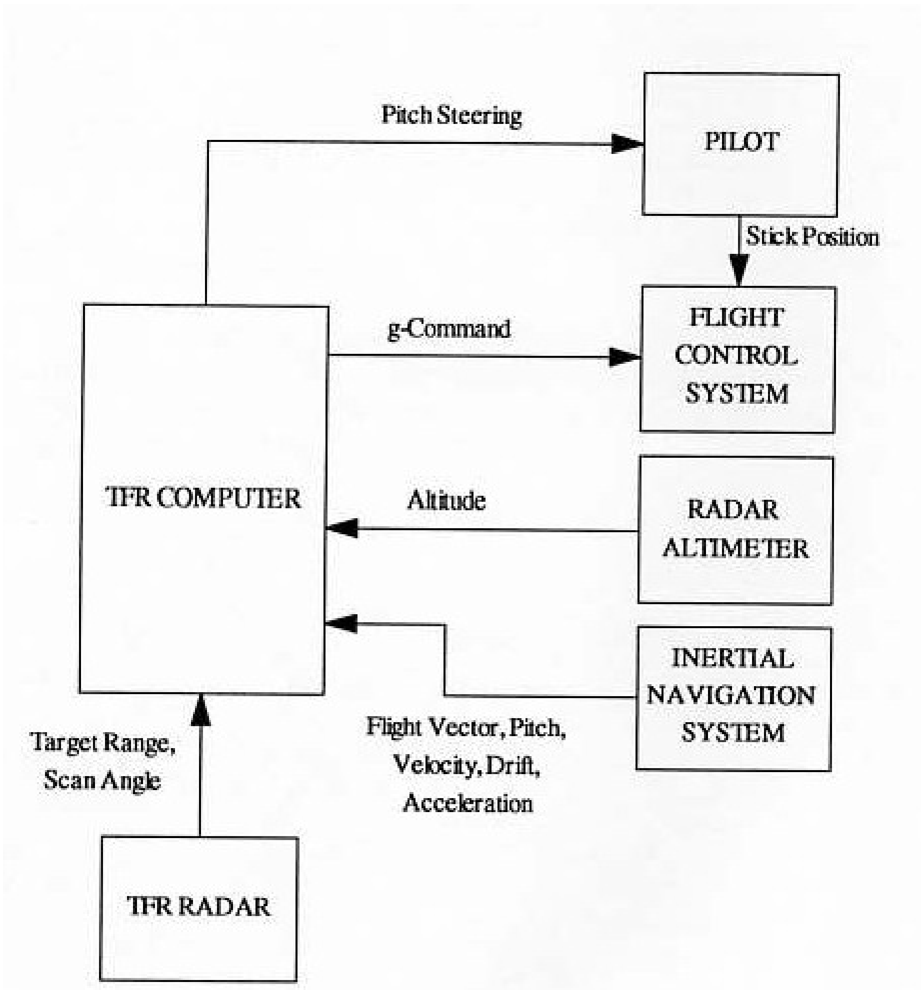

Figure 23. TFR Systems Interface [Ramey, 1994]

3.6 TFR Evolution

TFR systems have been in existence since the early 1960s. There have been many improvements in capabilities and safety margins. The early systems were analog systems employing vacuum tubes. As the years progressed, many technological advances were made. Systems moved to higher power, greater reliability, faster processing and more complex algorithms. A summary of some of the high points is shown below:

RF-4C, A-7	• Analog operation • Pulse-by-pulse processing • Template system
Original F-111	• Analog operation • Pulse-by-pulse processing • Angle Ssstem
Tornado, C-130	• Digital computer • Pulse-by-pulse processing • Angle system (modified)
Upgraded F-111	• Digital computer • Selected point processing • Terrain storage • Angle system (modified)
LANTIRN, MMR, MFR	• Digital computer • Selected point processing • Terrain storage • ADLAT algorithm

3.7 TFR Algorithm Evolution

There have been several approaches to the terrain-following algorithms over the years.

3.7.1 Template Algorithm

This is the approach patented by Bert Bechtel in 1959. This method is shown in the first diagram in Figure 24. This algorithm involves creation of a two-part virtual line in the space in front of the aircraft. The lower section is the desired set clearance, and the slope of the upper section is based upon the climb capacity of the aircraft. As the radar scans the space in front of the aircraft, it monitors all terrain that can be seen. As returns are collected, the range and angle to the terrain is collected and stored. If the terrain or other object crosses the template line, a pull up command is generated proportional to the range in front of the aircraft. As the terrain clears the template line, a push down command is generated to return to the original set clearance desired by the pilot. This system was implemented using analog processing prior to the advent of digital circuitry. [Woodward, Lagrange, 1979]

3.7.2 Angle Algorithm

Further work on the template algorithm produced the angle model, shown in the second drawing in Figure 24. This method uses sums of angles, which were suitable to the analog systems of the time, which predates digital computing. In this method, the lower line in the figure is the desired set clearance of the aircraft. The β in the figure is the antenna scan angle and θ is the pitch angle of the aircraft. When these are combined, you get an angle to the object. Ho is the desired set clearance and R is the range to the point of interest. For small angles, the angle can be approximated by Ho/R. The last factor is Γ, which is a margin factor to allow for the push-over point at the peak of the climb to not drop below the set clearance. This factor is tuned to the response of the aircraft. The algorithm was further refined to utilitize parts of the template approach and was tuned to only respond to objects in a relatively near range and ignore objects at large ranges.

3.7.3 Advanced Low Altitude Algorithm

The third method is the advanced low altitude or ADLAT algorithm. This method was developed at the start of the digital computation age. The basic method is to compute a parabola where the derivative is taken to give a 0 slope at the peak of the climb at the desired set clearance. This method's computations are based upon single terrain points and are continuously calculated as the aircraft approaches the peak. This method uses complex calculations, including square root functions, to compute the parabolas. Figure 18 shows the phases of flight and the probable flight path for this type of algorithm. As it shows, the set clearance can be viewed as an offset of the terrain path. Aircraft cannot generally make instantaneous flight angle changes and match the offset path, and as a result, the aircraft tends to exceed the desired set clearance when passing over an object.

3.7.4 Path Following Algorithm

The last method presented is the path-following algorithm, which requires a significant increase in computation power over the prior methods. In this method, the flight path is considered to be the terrain with the offset being the set clearance. This path is followed by making a tracking algorithm and correcting for the offsets as the flight passes over the obstacle. To accomplish this, a large number of terrain points are collected and the computation is constantly updated.

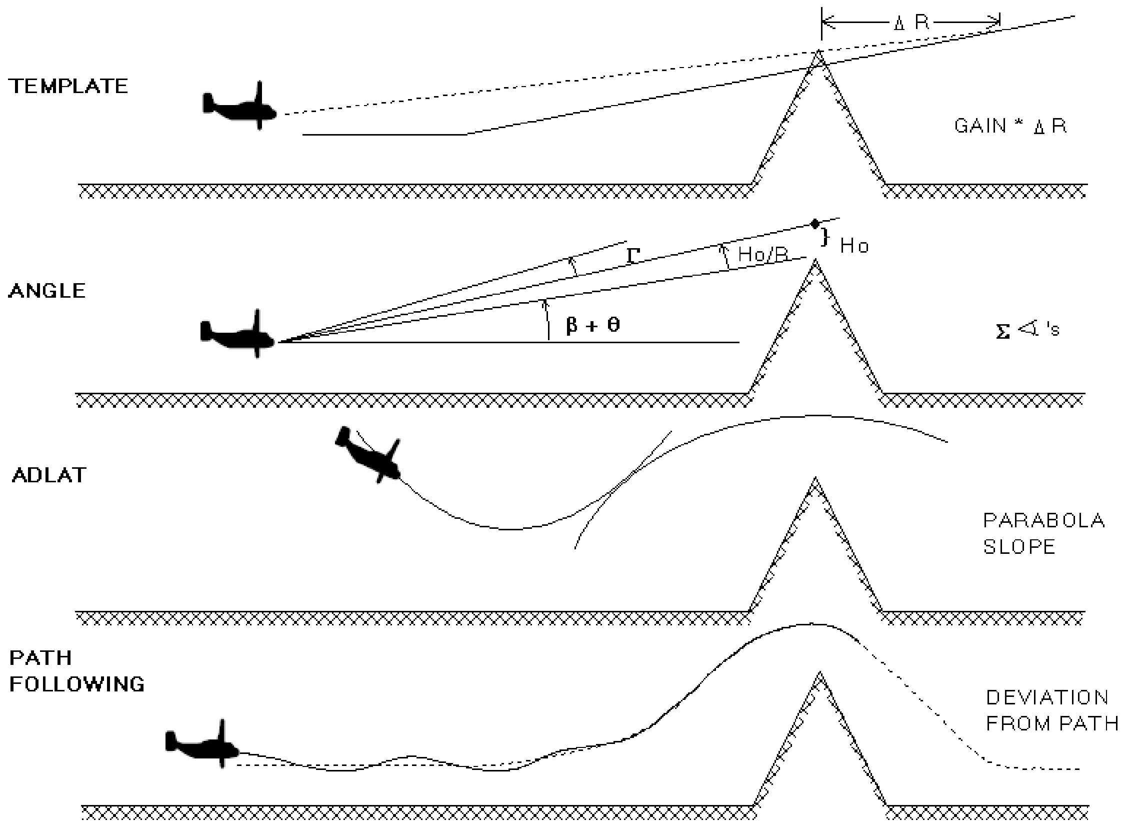

Figure 24. TFR Computation Approaches [Woodward, 2005]

3.7 Functional Requirements Future

As in all systems, there is always room for enhancements and system improvements. Some of the possible areas are listed below. These are generally a function of processor advances and willingness of the users to fund system improvements.

- Broader operational requirements
    - Azimuth control
    - Lower clearances
- Tighter control specifications
    - Lower average clearance
    - Better peak performance
- Enhanced system usability

    - Additional auxiliary unctions
    - More emphasis on user acceptance
- Improved radar characteristics
    - Detection of marginal terrain
    - ECCM/weather/low power
- Multi-sensor utilization
    - Digital map blending.
- Improved safety
    - Enhanced warnings and cautions
    - Less undershoot
    - Redundant processors
- Better visibility into system operation
    - Improved data collection and evaluation

Chapter IV
The Systems and Aircraft

4.1 The U.S. "AN" Electronic Equipment Identification System

Starting during the Second World War, the U.S. military established the "Army-Navy" (abbreviated to "AN") system for the identification of its electronic equipment. Currently, this system is applied to electronic equipment taken into the inventories of the USAF, U.S. Navy, U.S. Army and USMC. "AN" designations are also increasingly applied to military electronic systems of American origin but which have not been taken up by the country's military. "AN" identifiers are presented thus: AN/APG-66(V), in which APG identifies the equipment's installation type (first letter), the equipment's type (second letter) and its purpose (third letter); -66 indicates that the particular equipment is the 66th of its type included in the system; (V) indicates that the equipment can be configured to suit a number of platforms and/or system applications and 3 indicates that it is the third such variable configuration produced. The initial installation/type/purpose group can be read as follows:

Table 2. U.S. AN Electronic Equipment Identification System

Installation Identifier		Type Identifier		Purpose Identifier	
A	Piloted aircraft	**A**	Invisible light/heat radiation	**B**	Bombing
B	Underwater mobile/submarine	**C**	Carrier	**C**	Communications
D	Pilotless carrier	**D**	Radiac	**D**	Direction-finding/surveillance
F	Fixed ground	**G**	Telegraph/teletype	**E**	Release/ejection
G	General ground use	**I**	Interphone/public address	**G**	Fire control
K	Amphibious	**J**	Electromechanical/inertial wire covered	**H**	Recording/reproduction
M	Ground mobile	**K**	Telemetry	**K**	Computing
P	Portable	**L**	Countermeasures	**M**	Test/maintenance
S	Water	**M**	Meteorological	**N**	Navigation
T	Ground Transportable	**N**	Sound in air	**Q**	Special purpose
U	General utility	**P**	Radar	**R**	Receiver
V	Ground vehicular	**Q**	Sonar/underwater sound	**S**	Search/detection/range bearing
W	Water (surface/ subsurface applications combined)	**R**	Radio	**T**	Transmitting
Z	Unmanned/piloted air	**S**	Special/combination of	**W**	Automatic flight/remote

	vehicle combination		purposes		control
		T	Telephone (wire)	**X**	Identification/ ecognition
		V	Visible light	**Y**	Surveillance and control
		W	Armament		
		X	Facsimile/TV		
		Y	Data processing		

Accordingly, AN/APG-66(V)3 can be identified as the third variable configuration sub variant of the 66th airborne fire-control radar identified within the system. AN/APY-1 identifies the equipment as being the system's first registered airborne surveillance and control radar, while AN/APX-109(V) represents its 109th airborne radar identification/recognition system which, like APG-66(V), can be configured for variable applications. The reader should also be aware of the use of a suffix letter to identify succeeding generations of equipment. Thus, AN/APX-12A identifies the second generation of the system's twelfth ground mobile radar identification/recognition equipment to be produced.

4.2 The Radar Development Timeline

Figure 25 shows the evolution of TFR systems over the years as advancements in technology are made. This chart associates advances with specific systems, which are discussed in the following section.

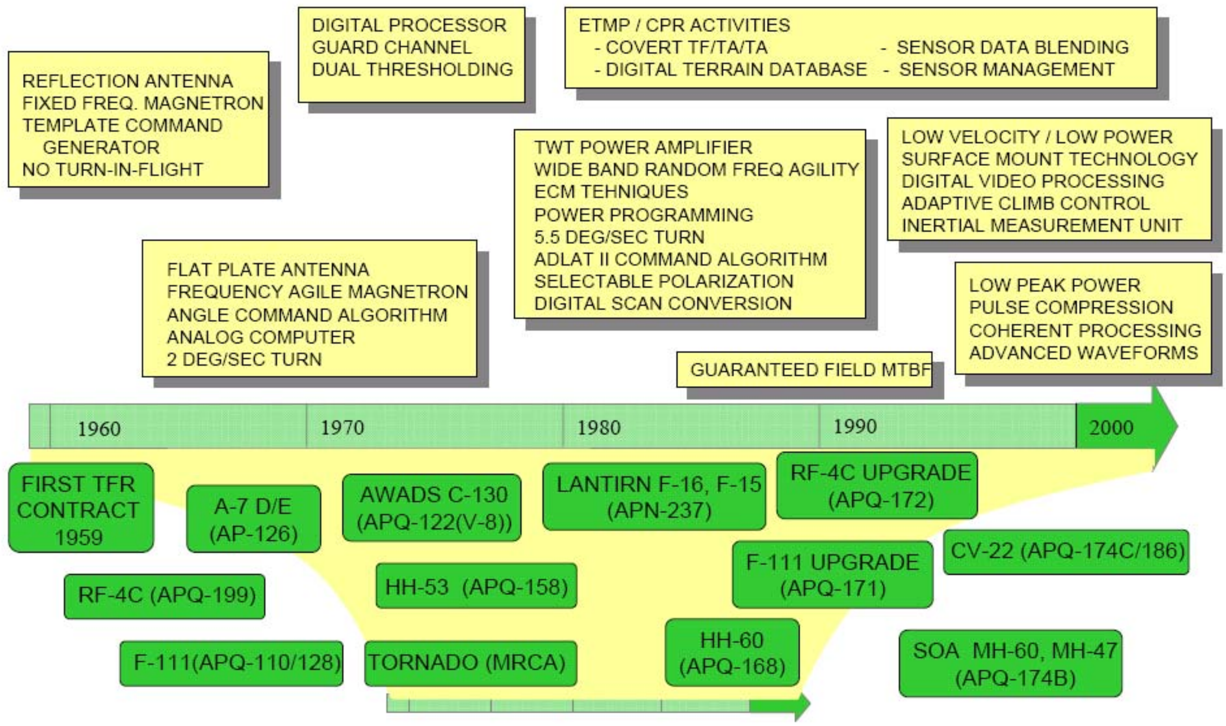

Figure 25. TFR Technology Evolution [Woodward, 2005]

4.2 The Radar Systems

Table 3. Terrain Following Radars

System	Original Manufacturer	Current Manufacturer	Estimated Quantity (if available)
AN/APQ-89			
AN/APQ-99	Texas Instruments	Raytheon	2000
AN/APQ-101	Texas Instruments	Raytheon	
AN/APQ-110	Texas Instruments	Raytheon	150
AN/APQ-115	Texas Instruments	Raytheon	
AN/APQ-116	Texas Instruments	Raytheon	500
AN/APQ-117	Texas Instruments	Raytheon	
AN/APQ-118	Norden	Northrup Grumman	
AN/APQ-122	Texas Instruments	Raytheon	
AN/APQ-126	Texas Instruments	Raytheon	1200
AN/APQ-128	Sperry		300
AN/APQ-134	Texas Instruments	Raytheon	300
AN/APQ-139	Texas Instruments	Raytheon	30
AN/APQ-141	Norden	Northrup	

		Grumman	
AN/APQ-146	Texas Instruments	Raytheon	150
AN/APQ-148/156	Norden	Northrup Grumman	
AN/APQ-154	Texas Instruments	Raytheon	
AN/APQ-158	Texas Instruments	Raytheon	10
AN/APQ-164	Westinghouse	Northrup Grumman	
AN/APQ-168	Texas Instruments	Raytheon	
AN/APQ-170	Systems and Electronics	Systems and Electronics	
AN/APQ-171	Texas Instruments	Raytheon	
AN/APQ-172	Texas Instruments	Raytheon	
AN/APQ-174	Texas Instruments	Raytheon	
AN/APQ-174B	Texas Instruments	Raytheon	
AN/APQ-186	Texas Instruments	Raytheon	
AN/APN-149	unknown		
AN/APN-165	Texas Instruments	Raytheon	
AN/APN-170	General Dynamics		
AN/APN-237	Texas Instruments	Raytheon	

4.3.1 AN/APQ-89

The AN/APQ-89 terrain-following radar system was tested in the T-2C Buckeye jet trainer aircraft produced for the U.S. Navy by North American Aviation (purchased by Rockwell, which later was purchased by Boeing). T-2C trainers were used by the Naval Air Training Command to conduct basic jet flight training for U.S. Navy and Marine Corps aviators. The trainer established an outstanding record of safety and reliability while providing training for more than 11,000 students to pilot 18 different models of Navy jet aircraft.

Figure 26. North American T2 'Buckeye' [Boeing]

4.3.2 AN/APQ-99

The AN/APQ-99 J-Band Forward-Looking Multipurpose Radar, manufactured by Texas Instruments, was used in the A-7A, RF-4B/C and the RF-101 aircraft. The contract award for this radar was in 1984 and flight trials started in 1986. This radar system was supplied to the U.S. military, Germany, Iran and Japan with an estimated quantity of 340 aircraft [Jane's Avionics, 1997].

The Ling-Temco-Vought A-7A /Corsair II is a carrier-based attack aircraft used primarily for tactical strike, close air support, and interdiction missions. In addition to service in the U.S. Navy, the U.S. Air Force, the U.S. Air National Guard, and several other nations flew Corsair IIs. Its first flight was Sept. 27, 1965. In comparison with the A-4 Skyhawk, which it was designed to replace, the A-7A was easier to maintain and was much more likely to survive combat damage. In addition, the A-7A had considerably longer range, making it possible to fly missions that the A-4 could not support.

Figure 27. Vought A7 Aircraft [Vought]

The McDonnell F-4 Phantom II was designed in 1953 to provide the U.S. Navy with an all-weather supersonic twin-jet capable of combining speed, maneuverability, bomb-load capacity, weight and power. The first basic version, designed for shipboard use by the U.S. Navy and the U.S. Marines, was the F-4B (first flight was on March 25, 1961), and 649 of these planes were delivered up to 1967.

Figure 28. McDonnell Douglas F4 Phantom [Boeing]

The McDonnell RF-101 Voodoo was a supersonic fighter designed to escort bombers and serve as a fighter bomber, an all-weather interceptor and a photoreconnaissance aircraft. It served during the Cuban missile crisis and during the Vietnam War. It began as the XF-88 all-weather interceptor (fighter), which first flew at Muroc Dry Lake Air Base in 1948. The two prototypes evolved into the F-101 Voodoo. McDonnell delivered 807 F-101 Voodoos, designed as long-range, twinjet fighters to escort bombers, attack distant targets and provide close support for ground troops.

Figure 29. McDonnell Douglas RF101 [Boeing]

4.3.3 AN/APQ-101

The AN/APQ-101 terrain-following radar was manufactured by Texas Instruments. No information on the radar systems or aircraft was available.

4.3.4 AN/APQ-110

The AN/APQ-110 was a Ku-band terrain-following radar manufactured by Texas Instruments. It replaced the side-looking AN/APQ-102 mapping radar manufactured by Goodyear in the McDonnell RF-4C Phantom II tactical reconnaissance aircraft, which went into service for the U.S. Air Force in 1964.

Figure 30. McDonnell Douglas RF4C [Boeing]

The AN/APQ-110 also was used in the General Dynamics F-111A Aardvark (the Air Force F-111 version), which went into service in 1967. The AN/APQ-110 was designed into the Grumman F-111B (the U.S. Navy version), but Congress refused to fund F-111B production in May 1968 due to the aircraft being too underpowered to fly from aircraft carriers.

Figure 31. General Dynamics F111 [The Military Factory]

4.3.5 AN/APQ-115

The AN/APQ-115 terrain-following radar system manufactured by Texas Instruments was used in the Lockheed Combat Talon C-130E Hercules, which primarily performed airlift missions. The aircraft, capable of operating from rough dirt strips, was the prime transport for air dropping troops and equipment into hostile areas.

Figure 32. Lockheed C130 Combat Talon [Lockheed Martin]

The AN/APQ-115 was also installed on the Vought A-7A Corsair II (Figure 27) carrier-based attack aircraft. It was used primarily for close air support, tactical strike and interdiction missions. The A-7A went into service in September 1965.

The General Dynamics F-111 Aardvark (Figure 31) and the McDonnell Douglas RF-4C Phantom II (Figure 30) aircraft also carried the AN/APQ-115.

4.3.6 AN/APQ-116

The AN/APQ-116 terrain-following radar developed by Texas Instruments was used in the Vought A-7 A/B/C Corsair II (Figure 27) version and the Lockheed C-130 Hercules (Figure 32).

4.3.7 AN/APQ-117

The AN/APQ-117 terrain-following & attack radar by Westinghouse was based upon Westinghouse's AN/APQ-109 fire control & search radar. The AN/APQ-117 was used in the McDonnell F-4D/E Phantom II. The F-4D entered operational service in April 1966 and was used primarily for with air to air interception duties. The F-4D boasted several new features including an improved bombing capability, better air-to-air range, and a redesigned equipment cooling system. The Navy procured the F-4D for the Air Force as it had the F-4C (Figure 28).

The F-4E, which took off on its maiden flight on June 30 1967, became the leading Phantom model, with 1,389 planes built. The first F-4E was delivered to the Air Force in October 1967. The F-4E, which was equipped with leading-edge maneuvering slats and weapons and radar controls that were optimized for dog fighting maneuvers, vastly improved the Phantom's air-to-air capabilities.

4.3.8 AN/APQ-118

The AN/APQ-118 terrain-following radar, manufactured by Norden, used in the MH-53H and AH-56A helicopters. The Sikorsky MH-53H Pave Low III is a CH-53A Sea Stallion rebuilt for deep commando insertions during nighttime operations. The MH-53H was the first version fully cleared for nighttime operations with the crew employing night vision goggles.

Figure 33. Sikorsky MH-53 [Sikorsky]

The Lockheed AH-56 Cheyenne was a prototype attack helicopter developed to replace the AH-1 Cobra, but it never went into production. Lockheed rolled-out the first prototype on May 3, 1967. Because of the advanced technologies in the AH-56 Cheyenne, the program ran into serious delays and cost overruns. Unfortunately, the Cheyenne experienced developmental difficulties with some of the new technology it employed. By the time the aircraft was ready for production in 1972, the Army was becoming interested in a helicopter with night and all-weather attack capability - a requirement that was not included in the Cheyenne contract.

4.3.9 AN/APQ-122

The AN/APQ-122 multimode (terrain-mapping/target-locating/navigation/weather) radar is manufactured by Raytheon Company (Raytheon acquired the Defense Systems business of Texas Instruments in 1998).

The AN/APQ-122 is a dual-frequency nose radar developed for use in the US Air Force Adverse Weather Aerial Delivery System (AWADS) program for installation in C-130E transport aircraft. This long-range navigation sensor is used for weather avoidance and navigation in supply dropping missions. The equipment provides ground-mapping out to more than 385 km, weather information up to 278 km and beacon interrogation up to 444 km when using the I-band frequency radar. J-band frequencies are used when short-range high-resolution performance and target location are required. In the J-band mode the radar provides a high-resolution ground map display to permit target identification and location for position fixing and aerial delivery missions. In this mode, the radar will detect and display targets with a radar cross-section of 50 m^2 while operating in rainfall of 4 mm/h.

In addition to the dual-frequency system designed for AWADS, designated AN/APQ-122(V)1, three other configurations have been developed. The AN/APQ-122(V)5 is a single-frequency I-band radar which has been developed as a direct replacement for the AN/APQ-59 radar used in C-130 and E-4B aircraft. Facilities include long-range mapping, weather evaluation and avoidance and rendezvous. A navigation training version of the AN/APQ-122(V)5, the AN/APQ-122(V)7, has been designed for use in the T-43A aircraft. Another dual-frequency radar, the AN/APQ-122(V)8, incorporates a terrain-following capability and is used on Combat Talon 1 MC-130 aircraft. [Jane's Avionics, 2005]

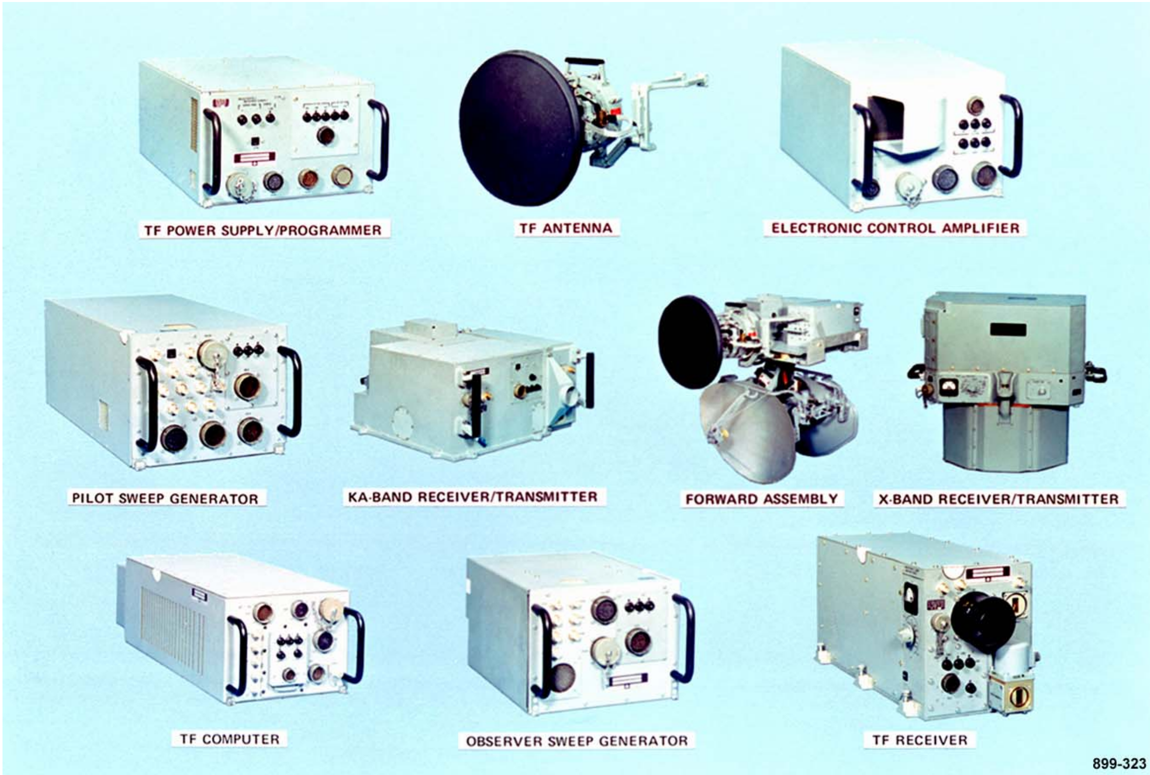

Figure 34. AN/APQ-122 Radar System [Raytheon]

The AN/APQ-122 multimode radar is used in the Lockheed MC-130E/H Combat Talon I and II (Figure 32). Both aircraft provide infiltration, exfiltration and resupply of Special Operations forces and equipment in hostile or denied territory. Secondary missions include psychological operations and helicopter air refueling.

The primary difference between the MC-130E and MC-130H involves the degree of integration of the mission computers and avionics suite. The Combat Talon I was conceived originally and developed during the 1960s, and although extensively upgraded in the 1980-90s, it still features analog instrumentation and does not fully integrate the sensors and communications suites. The Combat Talon II, designed in the 1980s, features an integrated flight deck, which improves crew coordination and reduces the crew complement by two.

The MC-130E/H has improved terrain-following/terrain-avoidance radar with increased reliability. Both aircraft feature terrain-following and terrain-avoidance radars capable of operations as low as 250 feet in adverse weather conditions. The acquisition strategy is to award a sole source contract to Raytheon.

During Desert Storm, the MC-130E Combat Talon I played a vital role. One-third of all airdrops in the first three weeks of the war were performed by MC-130s. Its primary role was psychological operations, as it air-dropped 11 BLU-82/B general-purpose bombs and flew multiple missions air-dropping and dispersing leaflets. Its secondary role was combat search and rescue. Following the first Persian Gulf War, MC-130s flew extensively in support of Operation Provide Comfort.

The AN/APQ-122 is used on The Boeing Company's KC-135A Stratotanker, whose principal mission is air refueling, carrying 200,000 pounds of aircraft fuel. It provides aerial refueling support to U.S. Air Force, Navy and Marine Corps aircraft, as well as aircraft of allied nations.

Figure 35. Boeing KC135 [Boeing]

The AN/APQ-122 radar system is also used on the RC-135A/C reconnaissance aircraft, which provides near real-time on-scene intelligence collection, analysis and dissemination capabilities. Initially employed by the Strategic Air Command to satisfy nationally tasked intelligence-collection requirements, the RC-135 fleet has also participated in every sizable armed conflict involving U.S. assets during its tenure.

The AN/APQ-122 is also used on the Boeing T-43A, a medium-range, swept-wing jet aircraft equipped with modern navigation and communications equipment to train navigators for strategic and tactical aircraft. The T-43A is the U.S. Air Force version of the Boeing 737 transport. The first T-43A was delivered to the Air Force in September 1973, and the last deliveries were made in July 1974.

Figure 36. Boeing T-43 [Boeing]

The Boeing E-4B also uses the AN/APQ-122 radar system. The E-4B evolved from the E-4A, which had been in service since late 1974. The first B model was delivered to the U.S. Air Force in January 1980, and by 1985 all aircraft were converted to B models. The E-4B, a militarized version of the Boeing 747-200, serves as the National Airborne Operations Center for the U.S. President and Secretary of Defense. In case of national emergency or destruction of ground command control centers, the aircraft provides a highly survivable command, control and communications center to direct U.S. forces, execute emergency war orders and coordinate actions by civil authorities.

Figure 37. Boeing E-4B [Boeing]

4.3.10 AN/APQ-126

The AN/APQ-126(V) is a forward-looking variable configuration airborne navigation and attack radar produced for the U.S. Navy A-7E and US Air Force A-7D aircraft. It operates in the J-band and its primary functions are ground-mapping, air-to-ground ranging and terrain-following/terrain-avoidance. The radar also features adverse weather look-through using selectable polarization, slaved antenna pointing in air-to-ground ranging and variable tilt control that allows the pilot to optimize ground map displays and highlight points of interest. The AN/APQ-126 is manufactured by Raytheon (originally developed by Texas Instruments). [Jane's Avionics 2002].

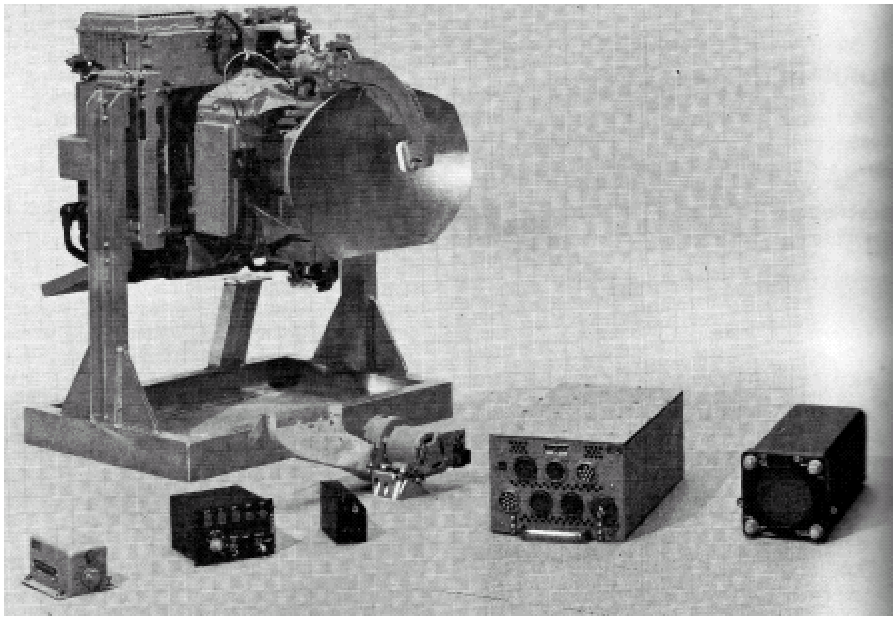

Figure 38. AN/APQ-126 [Jane's, 1990]

The system is used in the Vought A-7D/E Corsair II (Figure 27) aircraft, which went into service in 1966. It was designed as a lightweight attack aircraft to supplement and later replace the Douglas A-4 Skyhawk. From 1965 to 1983, more than 1,500 A-7s in several models were produced by LTV Aerospace Corporation (after 1976 under the name Vought Corporation). Vought A-7s have flown in combat roles in every campaign from Vietnam to Desert Storm. [Data from current operations in Iraq is restricted.]

The U.S. Navy also used the AN/APQ-126 on the North American Rockwell T-39D Saberliner. The TD-39 was used as a training aircraft for naval flight officers and radar operators.

Figure 39. North American T-39 [Boeing]

The AN/APQ-126 also was installed on the Lockheed AC-130E Pave Aegis gunship, which earned several unofficial nicknames including "Big Gun" and "Big Bertha" for its firepower. This U.S. Air Force jet flew its first combat mission in February 1972. It was used to intercept and destroy trucks carrying supplies from North Vietnam, Laos and Cambodia during the Vietnam War.

Figure 40. Lockheed AC-130A [USAF Museum]

The AN/APQ-126 is installed in the Sikorsky CH-53D Sea Stallion (Figure 33) used by the U.S. Marine Corps. The CH-53D is a medium lift helicopter designed for the transportation of equipment, supplies and personnel during the assault phase of an amphibious operation and subsequent operations ashore. It went into service in October 1966. Capable of both internal and external transport of supplies, the CH-53D is shipboard compatible and capable of operation in adverse weather conditions both day and night. The CH-53D is now filling a role in the Marine Corps' medium lift helicopter fleet.

The CH-53E Super Stallion is the U.S. Marines Corps' heavy lift helicopter. The CH-53D, along with the CH-46E, is slated for replacement by the MV-22 Osprey.

4.3.11 AN/APQ-128

The AN/APQ-128 J-Band terrain-following radar, a derivative of the earlier U.S. Air Force AN/APQ-110 version manufactured by Sperry, was used in the Vought A-7D/E Corsair II (Figure 27) and the General Dynamics F-111C/D Aardvark (Figure 31).

The General Dynamics F-111C was a sort of hybrid of the F-111A, F-111B and the FB-111A, designed for the government of Australia. The first F-111C was delivered on Sept. 6, 1968. The F-111D was a more advanced version of the F-111 with better navigation, improved air-to-air capability and newer turbofan engines. The first F-111D flew on May 15, 1970.

See other references in this paper to the Vought A-7D/E Corsair II.

4.3.12 AN/APQ-134

The AN/APQ-134 Ku-Band terrain-following radar was manufactured by Texas Instruments. It was used to upgrade the AN/APQ-110 terrain-following radar systems in the General Dynamics F-111A Aardvark (Figure 31).

4.3.13 AN/APQ-139

The AN/APQ-139 Ku-Band multi-mode radar; manufactured by Texas Instruments, was used in the Martin B-57G Canberra. The B-57 G model was specifically designed for night interdiction missions in Vietnam. The first B-57G entered service in mid-1970 and entered combat by late 1970 or early 1971. With the end of the Vietnam War approaching, the B-57Gs were withdrawn

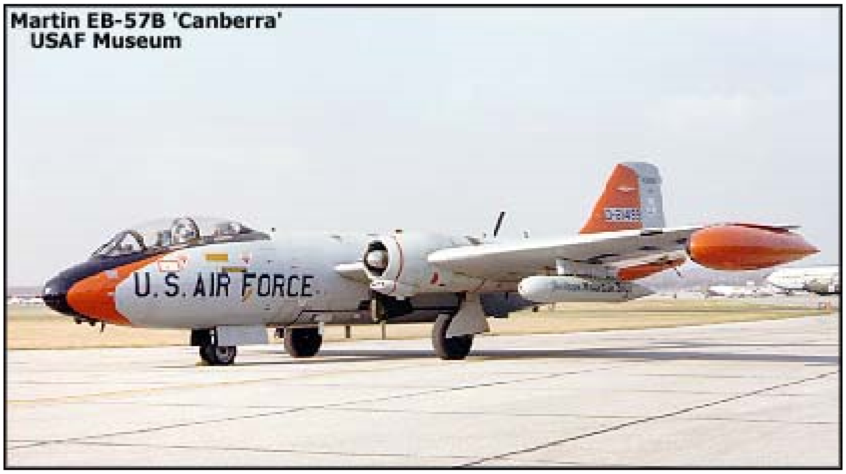

Figure 41. Martin EB-57B 'Canberra' [USAF Museum]

4.3.14 AN/APQ-141

The AN/APQ-141 terrain-following radar, manufactured by Norden, was fielded on the AH-56 and HH-53 Pave Low helicopters.

See earlier references in this paper to the AH-56 Cheyenne history.

The Sikorsky HH-53 Pave Low (Figure 33), nicknamed the "Super Jolly Green Giant," made its first flight at Wright-Patterson Air Force Based on March 15, 1967. The heavy-lift helicopter was used extensively during the Vietnam War for special operations and rescue of combat personnel, and later as a primary recovery of spacecraft in space operations.

4.3.15 AN/APQ-146

The AN/APQ-146 is a dual-channel, forward-looking, multimode radar developed for the F-111F. The radar's primary function is to provide proper commands to control the F-111 aircraft automatically at a preselected set clearance height above the terrain. This allows the F-111 to fly a low-altitude flight path following the earth's contours, thereby reducing the chance of detection. Each channel of the terrain-following radar system is identical, providing system flexibility and improving overall system reliability and mission success. The units of this radar provide the following modes of operation: terrain-following, situation, terrain-avoidance and ground map. The AN/APQ-146 was manufactured by Texas Instruments. [Jane's Avionics 1995]

There are two F-111 attack radar backup modes which may be selected by equipment external to the APQ-146. One is an air-to-ground ranging mode which uses the elevation monopulse resolution improvement capability of the TFR and is slaved in elevation to an externally generated position taken from the lead-computing optical sight, the azimuth axis being aligned with the drift angle. The other is a ground map backup

The first F-111F Aardvark (Figure 31) entered service in January 1972. It was a much improved version, with more reliable avionics, better targeting and much better power. F-111Fs spearheaded the U.S. attack on Libya on the night of April 14, 1986, striking targets in Tripoli with laser-guided bombs.

During Operation Desert Storm, the F-111F flew 2,500 sorties, destroyed 2,203 targets, including direct hits on 920 tanks, 252 artillery pieces, 245 hardened aircraft shelters, 13 runways, 113 bunkers, and 12 bridges. It was the last F-111 version produced. On the last night of the war, two F-111Fs delivered the hastily-devised GBU-28 "Bunker Buster" deep-penetration bombs against Iraqi command and control bunkers. These bombs could penetrate over 100 feet of earth or 22 feet of concrete. No F-111Fs were lost in combat during the first Persian Gulf War, a remarkable testament to its combat effectiveness.

In 1995-1996, the F-111Fs were all retired and placed in storage, ending the long service of the F-111 series with the U.S. Air Force.

4.3.16 AN/APQ-148/156

The AN/APQ-148/156 radar was manufactured by Norden for the Northrup-Grumman A-6 Intruder attack aircraft. This radar was a J-band multimode radar which was developed to combine the functions of the APQ-92 radar, which provided search and terrain-following/avoidance, and the AQP-112, which provided target tracking and ranging. The APQ-156 is a modification of the APQ-148 to accommodate the addition of a FLIR/laser target recognition attack sensor. [Jane's, 1990]

The A-6E (Figure 42) was an all-weather, two seat, subsonic, carrier-based attack aircraft. It was equipped with a microminiaturized digital computer, a solid state weapons release system, and a single, integrated track and search radar. The target recognition/attack multi-sensor (TRAM) version of the A-6E was introduced to the fleet in 1979. It was equipped with a chin turret containing a forward-looking infra-red (FLIR) system and a laser designator and receiver.

The A-6E proved once again that it was the best all-weather precision bomber in the world in the joint strike on Libyan terrorist-related targets in 1986. With Air Force FB-111s, A-6E Intruders penetrated the sophisticated Libyan air defense systems, which had been alerted by the high level of diplomatic tension and by rumors of impending attacks. Evading more than 100 guided missiles, the strike force flew at low levels in complete darkness, and accurately delivered laser-guided and other ordnance on target. Composite wing replacement and systems/weapons improvement programs maintained full A-6E combat systems capability, with initial operational capability realized in FY 88 with VA-75 deployment onboard USS John F. Kennedy (CV 67).

The December 19, 1996 launch of an A-6E Intruder from the aircraft carrier USS Enterprise (CVN 65) marked the last Intruder squadron to fly from the deck of an aircraft carrier. The Intruder Attack Squadron 75 of Carrier Air Wing 7, known as the “Sunday Punchers,” was decommissioned in early 1997. [FAS, 2005]

Figure 42. Northrup Grumman A6E 'Intruder' [FAS, 2005]

4.3.17 AN/APQ-154

The AN/APQ-154 terrain-following radar was manufactured by Texas Instruments for use in the Sikorsky HH-53C Pave Low helicopter (Figure 33), used by the U.S. Air Force. The CH-53C was initially employed for covert operations in Vietnam; later, eight CH-53Cs were used to provide battlefield mobility for the U.S. Air Force Mobile Tactical Air Control System. Forty-four upgraded HH-53C combat-rescue helicopters also served in Vietnam, beginning in 1969. These aircraft participated in the attempt to rescue American prisoners-of-war in the Son Tay raid of November 1970. The HH-53C remained in service into the late 1980s.

4.3.18 AN/APQ-158

The AN/APQ-158 is a multimode forward-looking radar used primarily for terrain-following/terrain-avoidance at low altitudes in the Pave Low III night/adverse search and rescue helicopter, the Sikorsky MH-53J. The equipment is similar to the AN/APQ-126, but is modified for compatibility with the unique helicopter characteristics and the Pave Low III mission requirements. The radar contains 15 line-replaceable units (LRUs), which provide the same basic modes of operation as the AN/APQ-126.

System upgrades have provided this radar with the ability to supply updates in all modes except terrain-following, and to perform terrain-following missions over very high clutter areas such as cities. The AN/APQ-158 Terrain-Following Radar is an improved version of the AN/APQ-126 manufactured by Raytheon. [Jane's Avionics, 2005].

The AN/APQ-158 is used in the Sikorsky MH-53J Enhanced Pave Low III heavy-lift helicopter (Figure 33), which is the largest and most powerful helicopter currently in the U.S. Air Force inventory. Under the Pave Low III program, the Air Force modified nine MH-53Hs and 32 HH-53s for night and adverse weather operations using the AN/APQ-158. The decision to upgrade to the Pave Low III was partly the result of poor performance by Navy RH-53D helicopters during the attempted rescue of American hostages in Iran in April 1980. The J model entered service in 1988.

The Pave Low's mission is low-level, long-range, undetected penetration into denied areas, day or night, in adverse weather, for infiltration, exfiltration and resupply of special operations forces. Pave Lows were the first allied aircraft to enter Iraq in the first Gulf War when they led Army AH-64 Apaches behind enemy lines to take out long-range radars that would have warned the Iraqi leaders of impending air strikes.

4.3.19 AN/APQ-164

The AN/APQ-164 was developed for the U.S. Air Force B-1B aircraft by Westinghouse (now Northrup Grumman). This radar combines technology from the F-16 AN/APG-68 radar and the Electronically Agile Radar (EAR) program of the US Air Force.

The B-1B radar generates data for navigation, penetration, weapon delivery, and for certain other functions such as air refueling. There are four modes in the AN/APQ-164 system that provide navigation capability. The primary mode is a high-resolution synthetic aperture radar mapping mode, backed up by a monopulse-enhanced real beam ground-mapping mode. The system also detects weather ahead and can display ground beacon returns over a real beam image. The penetration functions of the radar include automatic terrain-following and terrain-avoidance. For weapon delivery, the radar provides four different functions. The first is a velocity update mode, similar to a Doppler navigator, which generates velocity information for the inertial navigation system. Coupled with an accurate global positioning system receiver in the avionics system, velocity update produces a dynamic, precision antenna calibration correction. Second, there is a ground moving-target detection and tracking capability for both fast- and slow-moving vehicles. Third is a high-altitude altimeter function that provides a very accurate measure of local height above the ground. Fourth is a monopulse targeting mode that provides accurate height to the on-scene selected fixed target.

The synthetic aperture mode provides the operator with a high-resolution image of an area of ground that can be chosen by the avionics system or the operator. Long-range maps can be made and five different map scales displayed. The synthetic aperture mapping mode accepts the coordinates of a waypoint from the avionics system and makes a map centered on that point. To make an image, the antenna is electronically scanned to the waypoint location. The radar transmits a train of pulses, gathers data for the image, and then switches itself off. At the same time, the image is stored in the radar and presented on the display in a rectangular, ground co-ordinate display.

The radar provides the basic data required for automatic terrain-following. It scans the ground in front of the aircraft and measures the terrain in a range vs. height profile out to 19 km and stores that data in the computer. The profile data is sent across the multiplex bus to the terrain-following control unit where the data is used to generate climb/dive commands. This flight profile is then automatically fed into the pilot's flight control system. Since the radar is not continuously scanning in terrain-following, a very low update is used, helping to reduce the risk of detection. This rate is variable and depends upon aircraft altitude, maneuvers, groundspeed and terrain roughness. Under normal conditions, updates are made at 3 to 6 second intervals. However, if the terrain demands it, data can be gathered continuously.

The AN/APQ-164 in the B-1B is a dual-redundant system, with two complete and independent sets of LRUs, except for the phased-array antenna. This was the first airborne application of this technology for combat aircraft. Only one set of LRUs is used at a time, the other being maintained on standby.

The phased-array is an outgrowth of the antenna developed on the EAR program. It contains 1,526 phase control modules and allows virtually instantaneous beam movement to any point in the antenna field of regard. When the radar mission requires a forward, right or left region of regard, the antenna is physically movable to three different positions on a roll detent mount. The radar can, therefore, look off to either side of the aircraft or forward by rolling the antenna about an axis. The normal antenna position is looking forward. However, when the antenna is rolled to one side, the field of view extends from the aircraft nose back to about 115º, permitting a look off to the side of interest without having to change aircraft heading. Once physically moved to one of the three available positions, the antenna is locked into a detent. From the fixed spot, it can be scanned electronically ±60º in azimuth and elevation by means of a unit on the antenna called the beam-steering controller, which controls all 1,526 phase control modules. [Jane’s Avionics, 2005]

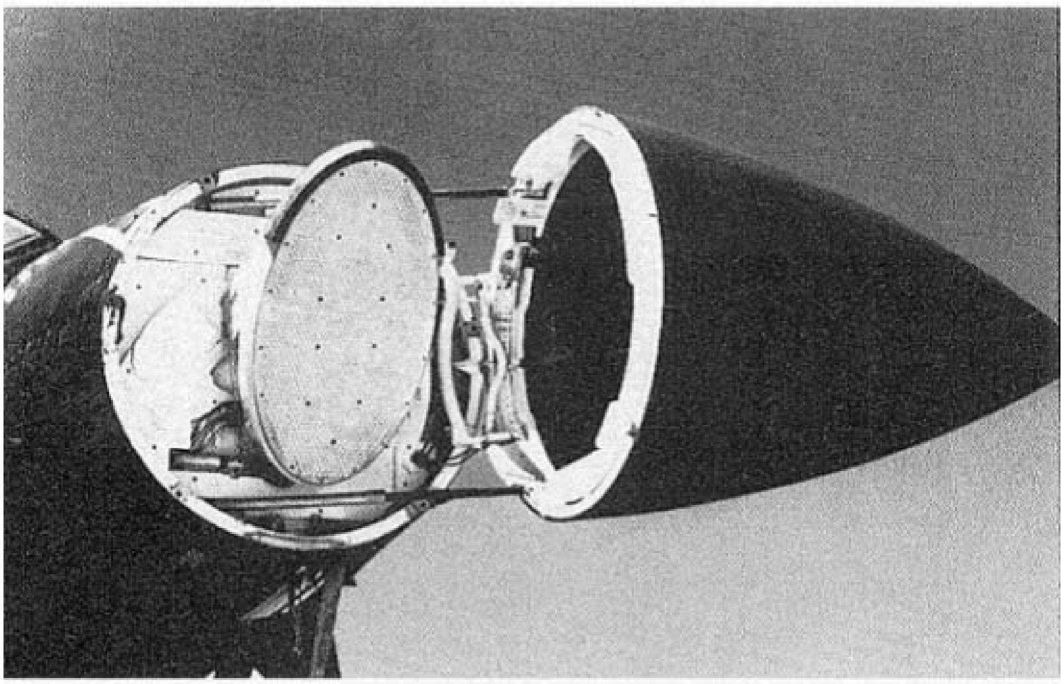

Figure 43. AN/APQ-164 [Jane's Avionics, 2005]

The B-1B Lancer was developed by Rockwell International, now Boeing Defense And Space Group, and is the U.S. Air Force long-range strategic bomber. The B-1B has the largest internal payload of any current bomber. The B-1B became operational in 1986, but in July 2001, the U.S. Department of Defense announced plans to cut its B-1B inventory from 92 to 60. The first aircraft was withdrawn from service in August 2002. Following Operation Iraqi Freedom, it was decided that there should be 67 aircraft in the fleet. [Jane's Radar and Electronic Warfare systems]

Figure 44. Rockwell B-1B 'Lancer' [USAF Museum]

4.3.20 AN/APQ-168

The AN/APQ-168 multimode radar is manufactured by Raytheon (Texas Instruments) and is used in HH-60D and MH-60K helicopters (the MH-60 has since been upgraded to the APQ-174B), and was proposed but not implemented for the V-22 Osprey. (See the V-22 Osprey background below).

The radar can operate in terrain-clearance, terrain-avoidance, air-to-air ranging and cross-scan modes, the latter combining ground-mapping or terrain-avoidance with terrain-following. A terrain storage facility permits the radar to have a reduced duty cycle, thereby reducing the probability of detection by enemy ESM equipment.

The system has increased electronic countermeasures resistance, improved weather penetration, better guidance in turning flight and a power management function for semi-covert. Extensive built-in test (BITE) provides a high degree of fault isolation and detection. The system is carried in a pod in the nose of the aircraft. [Jane's Avionics, 2005]

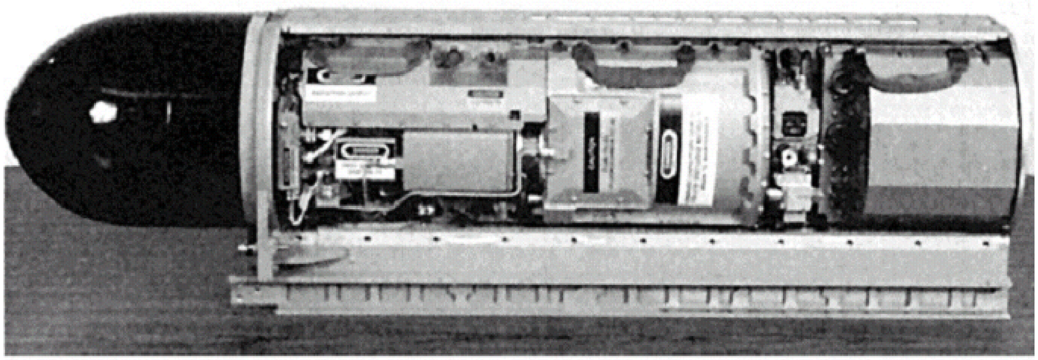

Figure 45. AN/APQ-168 [Jane's Avionics, 2005]

The Sikorsky HH-60D Night Hawk was a single UH-60A reconfigured as a combat search-and-rescue model for the U.S. Air Force with avionics for night/adverse weather operations, extended range, and unique combat rescue equipment. The UH-60A made its first flight on Feb. 4, 1984, but the program was cancelled.

Figure 46. Sikorsky HH/MH-60G [Sikorsky]

The Sikorsky MH-60K Black Hawk Special Operations Aircraft is designed for long-range, low-level penetration of hostile territory at night and in adverse weather. The first MH-60K performed its initial flight on Aug. 10, 1990, with the first of an initial production batch of machines performing its first flight on Feb. 26, 1992. The service careers of special operations machines tend to be kept quiet; however, MH-60Ks undoubtedly played significant roles in the Afghan intervention and the invasion of Iraq.

4.3.21 AN/APQ-170

Systems and Electronics Inc developed the AN/APQ-170 radar to equip 28 MC-130H Combat Talon II (Figure 32) aircraft procured for the U.S. Air Force Special Operations Forces. The radar has terrain-follow/avoidance capabilities, as well as ground map, weather and beacon modes. The AN/APQ-170(V)1 is a dual radar for redundancy and best performance in each mode. Delivery of the first AN/APQ-170-equipped aircraft took place in 1989.

The Lockheed Martin MC-130H Combat Talon II conducts infiltrations into politically denied/sensitive defended areas to resupply or exfiltrate special operations forces and equipment. These missions are conducted in adverse weather at low-level and long range. Flying as low as 250 feet, the MC-130H can perform high-speed airdrops and refuel helicopters in mid-air, proving its tough enough to handle the rigorous demands of Air Force spec ops. The first MC-130H Talon II was deployed in 1991. A Talon II evacuated Americans from the U.S. embassy in Liberia in 1996. The following year, Talon II participated in evacuation of Americans from U.S. embassy in Zaire.

4.3.22 AN/APQ-171

The AN/APQ-171 attack and terrain-following radar is an improved version of the AN/APQ-128/146). Manufactured by Raytheon, it is used in the General Dynamics F-111C/F Aardvark (Figure 31). The F-111E was identical to the F-111A, except for refined air-intakes to improve the engine's performance at speeds above Mach 2.2.

The AN/APQ-171 is the designation of the modified AN/APQ-146 series of airborne terrain-following radar systems which include AN/APQ-110, AN/APQ-128, AN/APQ-134 and AN/APQ-146 systems for F-111 aircraft. These modifications have been incorporated to improve reliability and maintainability on the F-111 and to provide a single radar configuration for all F-111 models.

Earlier versions of the AN/APQ-171 were the AN/APQ-146 designed for use in the F-111F, the AN/APQ-110 for use on the F-111A, F-111C and F-111E, the AN/APQ-128 for use on the F-111D and the AN/APQ-134 for use on the FB-111.

The AN/APQ-171 is a dual-channel forward-looking multimode radar developed for the F-111. The radar's primary function is to provide proper commands to control the F-111 automatically at a preselected set clearance height above the terrain. This allows the F-111 to fly a low-altitude flight path following the earth's contours, thereby reducing the chance of detection. Each channel of the terrain-following radar is identical, providing system flexibility and improving overall system reliability and mission success. The units of this radar provide terrain-following, situation, terrain-avoidance and ground map modes of operation.

There are two F-111 attack radar back-up modes which may be selected by equipment external to the APQ-171. One is an air-to-ground ranging mode which uses the elevation monopulse resolution improvement capability of the terrain-following radar and is slaved to an externally generated position taken from the lead-computing optical sight, the azimuth axis being aligned with the drift angle. The other is a ground map back-up mode where the terrain-following radar transmitter/receiver is routed through the attack antenna.

See earlier references in this paper for the F-111C, D and F versions.

4.3.23 AN/APQ-172

The AN/APQ-172 J-band terrain-following radar is the upgraded Raytheon version of the Texas Instruments AN/APQ-99.

The AN/APQ-172 is used in the McDonnell Douglas RF-4C Phantom II (Figure 28), which has been described earlier in this paper.

4.3.24 AN/APQ-174

The AN/APQ-174 multimode radar, manufactured by Raytheon, is used in the MH-60K, MH-47E, and MH-53 and was proposed for the MV-22, but was never fielded for this platform.

Figure 47. AN/APQ-174 [Raytheon]

The MV-22 Osprey tilt-rotor aircraft is the U.S. Marine Corps version for the amphibious assault transport of troops, equipment and supplies from assault ships and land bases. Initial operating capability for the MV-22 is planned for 2007.

Figure 48. Bell/Boeing V-22 'Osprey' [Bell]

The V-22 Osprey is a joint-service, medium-lift, multi-mission tilt-rotor aircraft developed by Boeing and Bell Helicopter. The tilt-rotor design combines the vertical flight capabilities of a helicopter with the speed and range of a turboprop airplane and permits aerial refueling and world-wide self deployment.

Boeing is responsible for the fuselage, landing gear, avionics, electrical and hydraulic systems, performance and flying qualities. Bell Helicopter Textron is responsible for the wing and nacelle, propulsion, rotor, empennage (complete tail system), ramp, overwing fairing and the dynamics.

The MH47-E is the U.S. Army Special Operations Forces variant of the Boeing MH-47 Chinook helicopter. Among U.S. and allied military helicopters, the Chinook is the only one that could fly with the full loads of troops and equipment needed for combat assaults over Afghanistan's high mountains and rugged terrain. The MH-47Es, with long-range fuel tanks, an aerial refueling probe, multimode radar and forward-looking infrared sensors, provided an extra edge for these missions. They can fly nearly 150 miles per hour just a few feet off the ground, at night and in bad weather.

Many of the MH-47E's technologies, such as its integrated cockpit displays, forward-looking infrared radar and multimode radar, continue to be tested in the Bell Boeing V-22 Osprey tilt-rotor aircraft.

See the previous discussion of the Sikorsky MH-60K Black Hawk and MH-53 Pave Low.

4.3.25 AN/APQ-174B

In 2003, Raytheon announced that it had received a $30.3 million contract from the U.S. Special Operations Command for the production of 30 APQ-174B multimode radar (MMR) systems with color weather mode (CWM) and for 48 CWM radar upgrade kits for existing APQ-174B MMR systems.

Under the contract, Raytheon will also install the 48 APQ-174B CWM radar upgrade kits and perform non-recurring engineering work.

The APQ-174B MMR with the CWM capability ensures the accurate display of adverse weather conditions to MH-47, MH-60, and CV-22 special operations helicopter aircrews.

The system, a derivative of the APN-237A LANTIRN terrain-following radar, was initially developed for the V-22 Osprey tilt-rotor aircraft. The APQ-174B MMR allows aircraft to perform special operations and search and rescue missions 24 hours a day during adverse weather conditions by using the following radar functions: terrain following, low power/low velocity TF, terrain avoidance, ground mapping, air-to-ground range finding, weather detection, beacon interrogation, and multiple cross scan modes.

4.3.26 AN/APQ-186

The AN/APQ-186 multimode radar manufactured by Raytheon is an improved version of the AN/APQ-174B. This version of the radar has all of the capability of the 174B with the addition of low power and low velocity modes, as well as allowing the transition of the aircraft from helicopter mode to airplane mode.

Figure 49. AN/APQ-186 [Raytheon]

The AN/APQ-186 is used in the CV-22 Osprey, the U.S. Air Force version of the tilt-rotor aircraft. The CV-22 is intended to replace the MH-53J and MH-60G and augment the MC-130 fleet for long-range missions for the U.S. Special Operations Command. Flight-testing for the CV-22 continues, and initial operating capability is planned for 2009.

4.3.27 AN/APN-149

The AN/APN-149 terrain-avoidance radar system was used in the Vought T-F8 Crusader. The F-8 Crusader was the first supersonic carrier-based fighter. The first prototype F-8 took off on March 25, 1955, from Edwards Air Force Base and it went supersonic in its maiden flight. The first F8U-1P flew on

Dec. 17, 1956 and it was the F8U-1P that did low-level photo reconnaissance during the Cuba crisis. The TF-8A was a two-seat version of the original F8U-1, envisioned for use as a trainer aircraft. Although it seemed promising during 1962, the "Twosader" never went into full-scale production because of U.S. Navy cutbacks.

Figure 50. Vought F8U-1T (TF-8A) [Vought, 2005]

4.3.28 AN/APN-165

The AN/APN-165 terrain-following/ground-mapping radar was manufactured by Texas Instruments for use in the OV-1.

With a very unique design, the Grumman Aircraft OV-1 Mohawk was the first turboprop plane to enter U.S. Army service. The OV-1 was built as a joint U.S. Army and Marine Corps project for a modern battlefield surveillance aircraft. The Marine Corps pulled out of the project before their prototype could be built, but the U.S. Army began placing its orders late in 1959 for the OV-1A and OV-1B.

Figure 51. Grumman OV-1C Mohawk [Pima Museum, 2005]

The first Mohawk flew for the Army in 1960 as a visual observation aircraft. It was soon pressed into service in Vietnam. Its primary mission was gathering and relaying information on enemy activities. The several of the aircraft were flown seven days a week, night and day from 1964 to 1996, keeping a constant vigil on North Korean activities along the Demilitarized Zone. The last Mohawk was finally retired in 1996.

4.3.29 AN/APN-170

The AN/APN-170 terrain-following radar manufactured by General Dynamics was tested in the A-4C, B-52 and B-58.

The Douglas A-4C Skyhawk is a versatile light attack-bomber that was a U.S. Navy first-line aircraft for many years. Unlike most other carrier-based aircraft, the A-4, with its relatively small wingspan, does not have folding wings. In 1959, the A-4C went into production, with improvements in cockpit layout, safety features, radar equipment, and all-weather flying capability. Six hundred and thirty-eight A-4Cs were built, making it the most numerous A-4 model produced. In Vietnam, A-4s were used both in close support of ground troops and in attacking other ground targets in North Vietnam.

Figure 52. Douglass A-4 Skyhawk [Boeing]

The Boeing B-52 Stratofortress bomber is capable of flying at high subsonic speeds at altitudes up to 50,000 feet. It can carry nuclear or conventional ordnance with worldwide precision navigation capability. A half century after first entering service, the BUFF (Big Ugly Fat Fellow) remains the backbone strategic bombing plane for the U.S. Air Force and is often still the first weapon sent against a combatant nation.

Figure 53. Boeing B-52 [Boeing]

The plane took its first flight on April 15, 1952. The huge plane had a 48-foot (five-story) dorsal fin and its wings had an area of 4,000 square feet. The first B-52As were delivered to the Strategic Air Command in 1954 where they became the primary airplane of the command.

In addition to delivering conventional and nuclear weapons, the B-52 has found other roles. It is used for ocean surveillance: two B-52s can monitor a 140,000-square-mile (364,000-square-kilometer) section of ocean in two hours, helping the Navy in anti-ship and mine-laying operations.

The Convair B-58 Hustler is the first supersonic bomber to be built by the U.S., entering service with the U.S. Air Force in 1960. Although the B-58 never fired a shot or dropped a bomb during conflict, it provided a key component of the Strategic Air Command's (SAC) deterrent capability during the 1960s. The aircraft served the SAC for only a decade before being put into storage.

Figure 54. Convair B-58 [USAF Museum]

4.3.30 AN/APN-237A LANTIRN

The AN/APN-237 LANTIRN is the first terrain-following radar system to be able to take advantage of digital technology. The radar is a sub component of the AN/AAQ-13 navigation pod.

The LANTIRN terrain-following radar team celebrated the delivery of the 800th system to prime contractor Lockheed Martin on August 28, 2001. Few Department of Defense programs have had the success and longevity as this program. Safety of flight has been the top priority, and the program has logged more than 1.5 million incident-free flight hours.

LANTIRN is a highly sophisticated navigation and targeting radar system that revolutionized the combat effectiveness of modern tactical aircraft. LANTIRN provides the capability for low-level missions down to 100 feet at night and under adverse weather conditions.

In 1980, the Lockheed Martin subcontracted Texas Instruments to provide the terrain-following radar for the LANTIRN system. Originally designed for the U.S. Air Force (USAF) F-16C/D and F-15E fighter aircraft, LANTIRN-derivative terrain-following radar systems have also been developed for other platforms including the U.S. Army Special Operations Aircraft (SOA) MH-47E and MH-60K and the U.S. Air Force CV-22 special operations Osprey tilt-rotor.

Figure 55. General Dynamics F-16 'Falcon' [USAF Museum]

Figure 56. McDonnell Douglas F-15E 'Strike Eagle' [USAF Museum]

The LANTIRN TFR program began its development phase in October 1980. Flight test evaluations began at Edwards Air Force Base in July 1983 on the F-16 and a production contract was awarded in July 1985.

In October 1986, one month ahead of schedule, the first LANTIRN production terrain-following radar system was delivered to the USAF. Production TFRs were initially deployed on the Block 40 F-16 aircraft, followed by the F-15E Eagle.

During the 1991 Gulf War, LANTIRN systems were instrumental in the critical opening days of the air campaign. LANTIRN opened the night window for around-the-clock operations deep into hostile territory. Mission effectiveness for LANTIRN Navigation Pods was reported to have been above 95 percent.

CHAPTER V
SUMMARY AND CONCLUSIONS

The United States military forces have had, and will continue to have, increased reliance upon technology. This has been stated in official policy and in procurement actions through the years. The edge that we maintain over our country’s adversaries is that of technology, because we cannot match the manpower capacities of less-capable governments. In light of this, there will be an almost constant need to increase the capabilities and safety margins for defense technology systems of this kind.

Budget constraints will force consolidation of systems on aircraft to perform multiple functions, instead of multiple radars doing individual functions. This is shown by the evolution of the terrain-following systems to have ground ranging capabilities, operational capability in adverse weather conditions, beacon interrogation, and ground mapping, which are all available modes in the newest of these systems, the AN/APQ-186 for the CV-22 Osprey aircraft.

Possible future capabilities could include functions such as wind shear detection to improve safety for landing aircraft. Air-to-air search and ranging would be another useful function to facilitate locating tanker aircraft for refueling in flight. With the emphasis on possible terrorism detection, maritime surveillance modes may be added to monitor and identify ships and other boats. Recently, the U.S. Pentagon unveiled that it is considering harnessing the high-power outputs of airborne radar systems for use as interdiction weapons. Airborne radar systems could potentially be used to interfere with the electronics of adversarial aircraft, missiles and threat-detection systems, rendering those systems ineffective.

Another area would be to find methods for reducing the transmitted power, which would greatly improve the stealthiness of the aircraft carrying these systems. The current systems rely on high-power transmitters to scan the ranges in front of the aircraft in order to provide the effective safety margins. This high-power transmission is equivalent to shining a bright floodlight on the ground in front of the aircraft. The probability of detection by ground forces from great distances is somewhat high, because the one-way transmit range of a radar is at least twice the round-trip range. Also, the possibility of detection by ground-based systems can possibly be much larger, since ground-based stations can employ antennas with much larger diameters in order to increase their sensitivity.

Along these lines, there has been some research performed upon passive terrain-following radar systems, in which the plane flies on autopilot. This type of system relies completely or partially upon the stored map databases to fly the routes. There are problems with completely passive systems, chief of which is the pilots' reluctance to cede aircraft control to automated systems. However, partially passive systems would seem to be possible and could gain acceptance by the pilots of the aircraft equipped with these systems.

Advances in computing power could also lead to improvements in the algorithms used to follow the terrain. This is shown by the past evolution of the algorithms discussed in other parts of this paper. The perfection of this process would be for the aircraft to follow the terrain with no deviation in set clearance. While this is not going to be completely possible on manned aircraft, because of the G-force limits that pilots and crew can take, it can become closer to the ideal on unmanned aircraft such as the Predator and Global Hawk, although never truly reachable since the number of G's approaches infinity.. Along this thought, having lower terrain settings is always a desirable goal, again limited by the processing power, range resolution and crew capabilities for safe flight.

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