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Systems Aspects of Digital Beam Forming Ubiquitous Radar

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14. ABSTRACT

This paper describes the general characteristics and potential capabilities of digital beam forming (DBF) ubiquitous radar, one that looks everywhere all the time. In a ubiquitous radar, the receiving antenna consists of a number of fixed contiguous high-gain beams that cover the same region as a fixed low-gain (quasi-omnidirectional) transmitting antenna. The ubiquitous radar is quite different from the mechanically rotating-antenna radar or the conventional multifunction phased-array radar in that it can carry out multiple functions simultaneously rather than sequentially. Thus it has the important advantage that its various functions do not have to be performed in sequence one at a time, something that is a serious limitation of conventional phased arrays. A radar that looks everywhere all the time uses long integration times with many pulses, which allows better shaping of Doppler filters for better MTI or pulse Doppler processing. The DBF ubiquitous radar is a new method for achieving important radar capabilities not readily available with current radar architectures. (See page v for the complete abstract.)

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Contents

Abstract

This paper describes the general characteristics and potential capabilities of digital beam forming (DBF) ubiquitous radar, one that looks everywhere all the time. In a ubiquitous radar, the receiving antenna consists of a number of fixed contiguous high-gain beams that cover the same region as a fixed low-gain (quasi-omnidirectional) transmitting antenna. The ubiquitous radar is quite different from the mechanically rotating-antenna radar or the conventional multifunction phased array radar in that it can carry out multiple functions *simultaneously* rather than sequentially. Thus it has the important advantage that its various functions do not have to be performed in sequence one at a time, something that is a serious limitation of conventional phased arrays. A radar that looks everywhere all the time uses long integration times with many pulses, which allows better shaping of doppler filters for better MTI or pulse doppler processing. The long observation times also allow the use of noncooperative target recognition methods (that require a long observation time) without interfering with other radar functions. In addition, such a radar for military purposes could operate within a wide bandwidth for providing electronic counter-countermeasures and other benefits. By employing a high duty cycle waveform (that spreads its energy over the temporal domain), along with a wide bandwidth (that spreads its energy over the spectral domain), and a low gain transmitting antenna (that spreads its energy over the spatial domain) such a radar can achieve a much lower probability of intercept than conventional radar architectures. The success of the ubiquitous radar concept depends on the extensive use of digital beam forming and digital signal processing. This report describes the overall concept of such a radar; discusses several different multiple radar functions that might be employed simultaneously with this radar architecture; illustrates how it can achieve a low probability of intercept; and reviews other benefits obtained with digital beam-forming. The DBF ubiquitous radar is a new method for achieving important radar capabilities not readily available with current radar architectures.

Systems Aspects of Digital Beam Forming Ubiquitous Radar

Introduction

The basic architecture of the long-range air-surveillance radar has changed little since it was first introduced in the 1930s just before World War II. Such radars are characterized by a highly directive antenna beam that is mechanically rotated in azimuth and which radiates a series of high peak-power pulses at a low duty cycle. Peak powers might be of the order of megawatts, duty cycles from about 0.001 to 0.01, antenna gains from approximately 30 to 40 dB, and antenna rotation rates from about 5 to 15 rpm, more or less. There have been many fine examples of radars produced in the past 60 years with such characteristics, but they have some fundamental limitations that radar designers have learned to accept. For example, the high peak power of the transmitted signal and the large antenna gain mean that the radiated signals from a military radar are readily detected and located (in angle) by hostile intercept receivers. Furthermore, the fixed rotation rate of the mechanically scanning antenna means that the revisit time is relatively long (a low data rate) and cannot be readily changed. The relatively long revisit times (usually many seconds) mean that a conventional air-surveillance radar cannot perform control of air-defense weapons that require data rates of the order of 10 observations per second.

Unlike the mechanically rotating-antenna radar, the flexibility and rapid beam steering of the conventional electronically steered phased array radar allow data rates high enough for weapon control. Thus the electronically steered phased array radar, such as Aegis[1] or Patriot[2], can perform the multiple functions of surveillance at long and short ranges with different data rates along with the tracking of multiple targets and weapon control. The conventional phased array, however, still radiates a high peak-power signal from a directive antenna so that it is readily detectable by a hostile intercept receiver at long range just as is the mechanically rotating-antenna radar. Furthermore, the conventional electronically steered phased array radar must perform its several functions *sequentially* so that they have to be shared one at a time. Thus it is not unusual in stressing situations to find that there might not be enough time for the phased array to perform all its important functions with the desired effectiveness. For instance, engagement of a hostile missile is a high priority function that would take precedence over a lower priority function such as above-horizon search.[3] When engaging a hostile missile, for example, the radar's above-horizon search function has to be stretched out in time (longer revisit times) and/or the size of the above-horizon surveillance region reduced. The difficulty caused by time sharing of functions has sometimes been expressed as "there are not enough microseconds in a second to do all that is needed with a single multifunction phased array radar."

Over the years the military radar community has learned to live with the limitations of an air-surveillance radar that employs a mechanically rotating antenna. The military radar community has also learned to accommodate the limitations of an electronically steerable phased array. But there is no fundamental reason why one has to be bound by these limitations. The *ubiquitous radar* as described here does not suffer these drawbacks. It can perform multiple functions *simultaneously* and its signals can be much more difficult to intercept than previous LPI (low probability of intercept) radar concepts. In addition, the nature of the ubiquitous radar architecture allows several other desirable capabilities not readily obtained with conventional radars. The many attractive features of a ubiquitous radar are now becoming more practical to achieve because of the ever increasing capabilities of digital signal processing (DSP) and digital beam forming (DBF). In addition to the benefits offered by the ubiquitous radar for military applications, the concept also has advantages in the civil use of air-traffic control radar and meteorological radar.

This report will describe the principle of the ubiquitous radar, its capabilities not available with conventional radars, and indicate some of its potential applications.
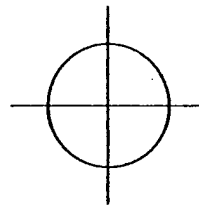
Concept of the Ubiquitous Radar

A ubiquitous radar is one that looks everywhere all the time. It does this by using a low-gain omnidirectional or almost omnidirectional transmitting antenna and a receiving antenna that generates a number of contiguous high-gain fixed (nonscanning) beams, as sketched in Fig. 1. For convenience of discussion, the radar is considered to be 2D; that is, it provides the range and azimuth angle of a target echo, but not elevation angle. There might be, for example, 200 to 300 individual receiving beams to cover 360 degrees in azimuth. The use of a low-gain omnidirectional transmitting antenna reduces the radiated peak power by a factor equal to the number of receiving beams. The reduced peak power radiated because of the low transmitter antenna gain, however, requires that a longer integration time be employed to receive the same amount of energy from a target as does a scanning directive antenna used for both transmitting and receiving. For example, if a rotating directive antenna had a revisit time of four seconds, the integration time at each receiving beam of a ubiquitous radar would also have to be four seconds, assuming no integration loss. Such a long integration time would be difficult to achieve with analog integration circuitry, but it can be obtained with digital integration.

In the military application of ubiquitous radar, there are two other characteristics that can be added to improve military utility, but which are not

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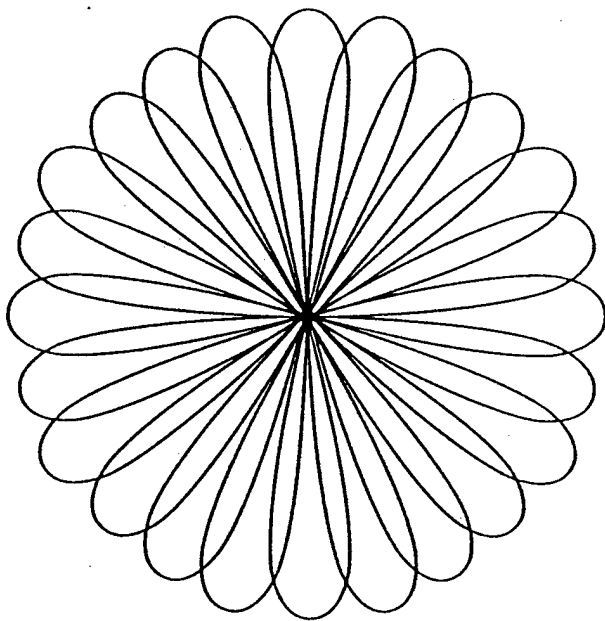
(a) Multiple receiving beams   (b) Omni transmitting
pattern

Fig. 1 - Antenna patterns for ubiquitous radar.

an inherent part of a ubiquitous radar that looks everywhere all the time. These are (1) high duty cycle waveforms and (2) the use of a larger portion of the spectrum than normally needed to accommodate the signal bandwidth. Both can be important for military radars that are subject to electronic countermeasures, detection and location by EW (electronic warfare) intercept receivers, and attack by antiradiation missiles (ARM). The use of a wide portion of the frequency spectrum has advantages for thwarting electronic countermeasures as well as providing the means for performing a measurement of target height based on multipath (without a 3D radar) and obtaining the radial profile of a target.[4,5] When one spreads the radiated signal energy in the temporal domain (with a high duty cycle), in the spectral domain (simultaneous operation in several portions of the frequency spectrum), and in the spatial domain (ubiquitous radar with omnidirectional transmit antenna), the radiated peak power can be many orders of magnitude lower than that of a conventional low duty-cycle radar that uses a scanning high-gain antenna. This characteristic of the ubiquitous radar discussed here makes the radiated signal difficult to detect by a conventional intercept receiver or antiradiation missile receiver.

The basic concept of a ubiquitous radar is easy to describe, but its implementation depends on exploiting the full capabilities offered by digital beam forming and digital signal processing. A simple block diagram is shown in Fig. 2. "Simple" means that much detail has been omitted. At each antenna element of the receive phased array antenna there is a receiver whose analog signal is digitized by the A/D converter. The significant difference in this system architecture from previous phased array radars is that once the digital numbers are obtained at each element, they can be used for many purposes simultaneously. Spatial beam forming is done first to provide N fixed receiving beams. (In digital beam forming there is no actual radiation pattern in space. The "pattern" resides in the computer and is evident as the variation of the output response of the signal processor as a function of the angle of arrival of the received signal.) At the output of each beam there are multiple digital signal processors to simultaneously provide the various radar functions.

The type of radar described in this paper is significantly different from previous military phased array radars because (1) it can perform multiple functions simultaneously and (2) its radiated signal can be considerably more difficult to intercept because of its much lower peak power. These two capabilities of a ubiquitous radar are discussed in the next two sections.

Simultaneous Multiple Functions

The various functions performed by a multifunction air-defense radar system usually have different ranges and different data rates. The ubiquitous radar
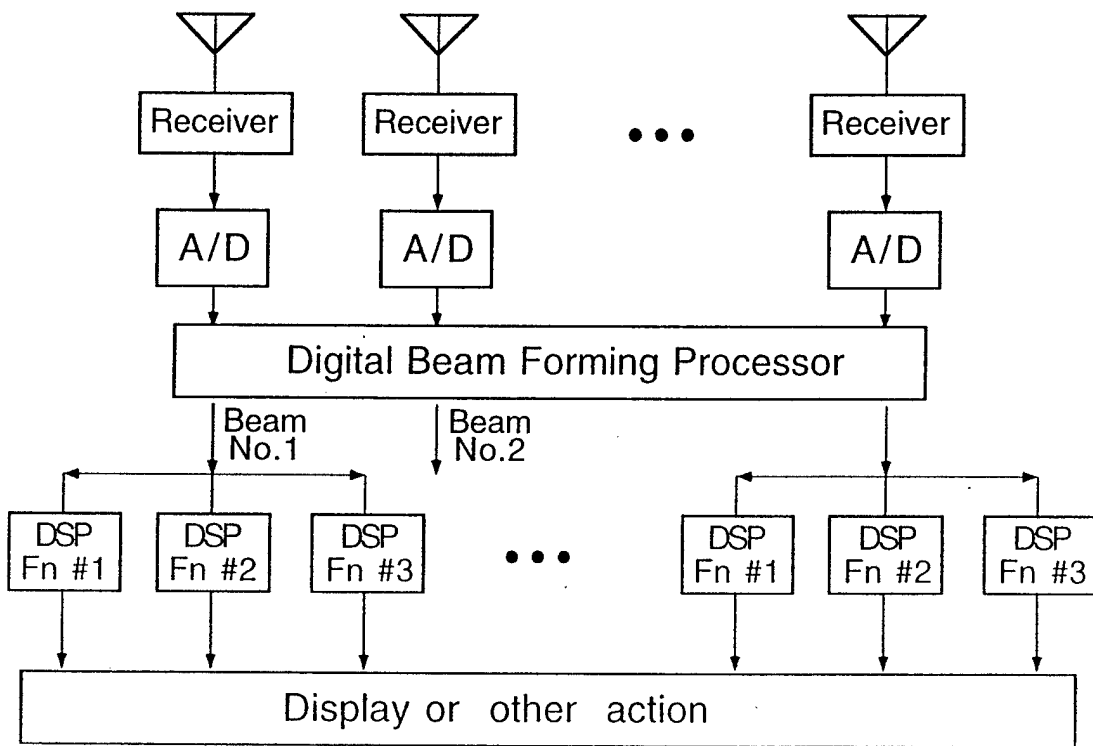
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Fig. 2 - Simple block diagram of a ubiquitous radar.

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concept usually allows these multiple functions to be performed simultaneously by using multiple (independent) processors, each designed to perform its own particular function. Of the many attractive features of the ubiquitous radar concept, perhaps the most important is its ability to perform simultaneous multiple functions. In this section, several of these functions will be briefly discussed using military air defense as the model.

An air defense radar might have to perform the following:
- *Long range surveillance at low data rate.* The revisit time might be 10 or more seconds. The range to a target might be from 100 to over 200 nmi.
- *Surveillance and target acquisition at medium ranges.* Medium ranges might be below about 100 nmi and revisit times about 4 s.
- *Short-range surveillance (pop-up targets).* This might be at ranges from 10 to 20 nmi or less, with revisit time of about one second.
- *Weapon control.* A high data rate (short revisit time of about 0.1 s) at short and moderate ranges, up to 30 to 40 nmi (but could be more).
- *Noncooperative target recognition.* This is desired at any range and can require relatively long dwell times.

The above numbers are not meant to be precise and are subject to revision depending on the application. The purpose of providing them is to indicate that the functions that have short revisit times are generally at short range and those that require long revisit times usually are at long ranges. Thus in a ubiquitous radar, the different data rates are obtained by integrating a different number of pulses. (The terms "data rate," "revisit time," and "integration time" are often used interchangeably in this report. A high data rate implies a short revisit time.)

In the example given in this section the radar is (somewhat arbitrarily) assumed to be designed to have a four second data rate at a range of 140 nmi and has to detect a target with a radar cross section of one square meter. Targets at shorter ranges can be detected with fewer pulses integrated (because the received echo power increases inversely as the fourth-power of the range) and therefore the revisit time can be less. Targets at longer ranges can be detected with a longer revisit time by performing long-term integration.

Surveillance and weapon control at middle ranges. By decreasing the integration time as a function of decreasing range the received echo signal power, and hence the probability of detection, can be maintained somewhat constant with decreasing range. With coherent integration, the 4 s revisit time at 140 nmi can be reduced to 0.25 s at 70 nmi and to 16 ms at 35 nmi. A typical data rate for weapon control in an air-defense system is 10 Hz, which is a revisit time of 0.1 s. A 0.1 s revisit time is obtained at a range of 55 nmi. Thus the ubiquitous radar that has a revisit time of 4 s at 140 nmi will have a data rate suitable for weapon control at ranges of 55 nmi and below.

It was assumed in the above that coherent integration was used. If noncoherent integration were employed instead, the range at which the revisit time is 0.1 s is less than that indicated above for coherent processing. With 0.1 s integration time and a prf of 350 Hz the number of pulses integrated is 35. The theoretical noncoherent integration loss for 35 pulses is about 3.5 dB and its integration improvement factor is about 16. With noncoherent integration, therefore, the range at which the revisit time becomes 0.1 s is about 45 nmi.

Short-range surveillance. A low-altitude sea skimmer missile flying at 2 m over the water might not be seen by a surface-based radar until it is well within 10 nmi of the radar (depending on propagation conditions). A radar that can detect a 1 m^2 target at 140 nmi with a 4-s revisit time can detect the same size target at 100 nmi with a 1-s revisit time. (Coherent integration is assumed.) Then there is enough echo signal energy at 10 nmi to detect a 10^{-4} m^2 target with a 1-s revisit time, assuming that doppler signal processing is used that provides an adequate signal-to-clutter ratio. If the radar requires a 0.1-s revisit time to guide a defensive missile to an intercept, the minimum detectable radar cross section is then 10^{-3} m^2. If it were really important to place a 10^{-4} m^2 cross section target in track with a 0.1 s revisit time, that could be done at a range of about 5.6 nmi. Coherent integration is assumed here since at short ranges doppler processing (which is coherent) would likely be used in order to detect moving targets in clutter.

Surveillance at long range. It is sometimes acceptable in air defense systems to allow the revisit time at long ranges to be longer than four seconds. Things don't usually change as fast at long range as they do at short range, and there is more time available to react than when a target is at short range. Air defense systems can, but seldom do, engage air targets at long range since long-range missiles are needed and there must be highly reliable target-identification (which might be harder to achieve at long ranges). Since the received echo signal power varies as R^{-4} (R = range), at ranges longer than 140 nmi the integration time can be made longer than 4 s in order to compensate for the smaller echo signal. With a pulse repetition frequency (prf) of 350 Hz and a 10 s integration time, assuming coherent (predetection) integration with no loss, the range of the radar will be 176 nmi, as indicated in Table 1. An integration time of 20 s gives a range of 209 nmi. If noncoherent integration is used instead of coherent integration, Table 1 indicates that the range will be 173 nmi with 20 s integration time and 200 nmi for 60 s integration time. The ranges will be in-between the two values in Table 1 if a combination of coherent and noncoherent integration were used.

In Table 1 the range for 4-s integration time is taken to be 140 nmi when either coherent or noncoherent integration is used. With 1400 pulses received from a target, noncoherent integration has an integration loss of about 9.6 dB, which corresponds to an integration improvement factor of 154 (or 21.9 dB). In a conventional radar with a mechanically rotating antenna

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and, for example, a 1.5 deg beamwidth and a 4-s revisit time (15 rpm rotation rate) there will be about 6 pulses received from a target. The noncoherent integration loss is about 1.2 dB. Thus at a range of 140 nmi the ubiquitous radar with noncoherent integration requires 9.6 - 1.2 = 8.4 dB more power than a conventional rotating radar also with noncoherent integration.

Table 1 RANGE WITH LONG-TERM INTEGRATION
350 Hz prf, nonfluctuating target echo

Integration time, s	Range, nmi, with coherent integration	Number of pulses integrated	Noncoherent integration improvement factor	Range, nmi, with noncoherent integration
4	140	1400	154	140*
10	176	3500	245	157
20	209	7000	360	173
30	232	10,500	443	182
40	249	14,000	520	189
60	275	21,000	645	200

* This assumes the power has been increased to give the same range as with coherent integration.

It would seem from the numbers given in Table 1 that it might not be worth integrating beyond 20 or 30 s, even with coherent integration. Also, the large losses that occur with noncoherent integration with integration times greater than 4 s might not be acceptable.

It might be concluded that a ubiquitous radar can employ a longer integration time at long ranges if a higher transmitter power is to be avoided (as for low probability of intercept) and the added complexity of longer coherent integration time can be tolerated.

Doppler processing. All modern air-surveillance radars use some form of doppler processing, such as moving target indication (MTI), in order to detect aircraft targets in the presence of stationary surface-clutter echoes. These clutter echoes may be from the land or sea and can be many orders of magnitude greater than the target echo. Surface clutter echoes are not usually seen at long ranges since they are below the radar horizon. The maximum range at which clutter echoes might be detected depends on the nature of the terrain (for example, large mountains) and the propagation conditions (especially ducting). At long ranges where there is no clutter the ubiquitous radar need not employ doppler processing.

In regions of moderate clutter, such as might occur at the longer ranges where neither mountainous nor urban clutter are encountered, a simple three or four pulse canceler might be all that is required as the doppler filter. At shorter ranges where the clutter echoes might be large and where it is important to have large MTI improvement factors to detect low cross section missiles and aircraft, a more complicated doppler filter might be needed. Such a filter will have to process many pulses in order to achieve a desired frequency response function.

Since the beams of a ubiquitous radar stare in each direction all the time, it has a considerable advantage in detecting targets in clutter over conventional MTI radars since it has many more pulses available. More pulses mean more degrees of freedom for the designer to work with in order to shape the filter response. As before, consider a conventional rotating-antenna radar with a pulse repetition frequency of 350 Hz, a 1.5 degree azimuth beamwidth, and an antenna that rotates 360 degrees in four seconds. There are about six pulses received from each target. Now consider a ubiquitous radar that has to detect a low altitude missile at short range with a revisit time of 0.1 s. The number of pulses available is 35, which provides more freedom than would just six pulses to design suitable MTI doppler filters that reject clutter and pass desired targets. At ranges where the revisit times are greater than 0.1 s, the number of pulses will be much larger and even better filters can be obtained. The design of doppler filters when a large number of pulses are available can be different from the design of the conventional MTI radar, so that different procedures might be considered for using the large numbers of pulses available with a ubiquitous radar. (For example, it might be desirable to divide a large number of pulses into smaller subgroups, process each smaller subgroup coherently using a doppler filter, and then combining the outputs of the subgroups noncoherently. Based on the previous assumptions, at a range of 100 nmi, the ubiquitous radar can detect a 1.0 m^2 target by using a one second integration time. There will be 350 pulses available. They might be divided into ten subgroups of 35 pulses each. The 35 pulses might be processed coherently to provide doppler filtering, and then the outputs of the 10 subgroups can be processed noncoherently to achieve the required signal-to-noise ratio.)

At the higher radar frequencies, a higher prf is usually needed in order to avoid excessive blind speeds (where moving targets are not detected) and reduced doppler space. When high-prf and medium-prf pulse doppler radars are used for this purpose, multiple pulse repetition frequencies have to be employed in order to resolve range ambiguities and obtain the correct value of range. The same can be done with a ubiquitous radar; but if multiple frequencies are used, as has been suggested earlier in this report, they can resolve the range ambiguities in a manner similar to using multiple prfs.

Rapid target acquisition. To establish a track with a conventional rotating antenna air-surveillance radar usually requires that the target be detected on a minimum of three scans of the radar. With a four-second revisit time the time to establish a track is from 8 to 12 s after the first detection of the target. Conventional phased array radars with rapid, agile beam-positioning can employ a fast "look-back" at the target after initial detection and can acquire a target much faster than can a radar with a mechanically scanning antenna. The conventional phased array in performing look-back, however, cannot perform any of its other multiple functions when it is so occupied. A ubiquitous radar, however, that looks everywhere all the time can do something similar, without reducing the performance of other radar functions.

Noncooperative target detection (NCTR). NCTR methods based on radar generally need a much longer observation time than the usual time-on-target required for detection in noise. A conventional phased array can stare at a target for as long as required to make a target recognition, but it does not usually have the luxury to do so because of the need to perform other radar functions within the necessary time available. The ubiquitous radar can provide the longer observation times required for NCTR without interfering with other functions.

Inverse SAR (ISAR) has been successful for the recognition of the class of a ship.[6] A ship's natural pitch, roll, and yaw motions as it travels through the sea provide the change in aspect required for successful imaging. Applications requiring ship recognition usually can tolerate the longer observation time (perhaps many tens of seconds) necessary to produce images suitable for NCTR. Aircraft NCTR using ISAR, however, is different. The recognition of aircraft with ISAR also requires a long observation time since the target has to change its aspect sufficiently to achieve the necessary cross-range resolution required. With conventional radar, the high speeds of aircraft and their relatively smooth courses do not usually allow the long times of observation needed for ISAR NCTR. On the other hand, the ubiquitous radar that stares in the same direction all the time can be patient until an aircraft, even on a straight-line course, changes aspect sufficiently or the aircraft makes a maneuver that allows an ISAR image to be formed.

The recognition of aircraft type based on the modulation of the radar echo produced by the rotating jet engine (*jet engine modulation,* or JEM) also requires more time than that normally needed for target detection.[7] The conventional phased array can have sufficient observation time for NCTR, but it will tie up the radar for a time longer than might be desired for a multifunction air-defense radar. Since the ubiquitous radar can perform its various functions in parallel, it can also perform NCTR without time sharing with other functions. A similar argument can be made for performing the related function of battle damage assessment.

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The ability of a ubiquitous radar to have a long observation time without sacrificing other radar capabilities is important for the detection and recognition of hovering helicopters that rise up above the masking terrain and remain in view for only a short time.[8,9] NCTR of helicopters is possible since helicopters produce large but short-duration radar echoes, or "flashes," every time their rotating blades are aligned perpendicular to the radar line of sight. These flashes are not usually seen by a conventional radar unless its antenna beamwidth is broad, its antenna scan rate is low, and its pulse repetition rate is high. Otherwise, the flash might occur when the scanning radar antenna beam is not in a position to see it. A radar that looks everywhere all the time, however, would not only detect the flash from the helicopter blade, but it would be able to observe a series of flashes over time that would reveal something about the type of helicopter.[10]

Because of the longer observation time available with a ubiquitous radar, it should be able to distinguish a chaff decoy, and perhaps even an active decoy, from a real target by examining the statistics of the echo over a period of time. It should also be possible to recognize birds by their characteristic wing-beat modulation.

Reduction of the Interceptability of the Ubiquitous Radar Signal

This section discusses the ability of a military ubiquitous radar to have a much lower probability of being intercepted by a hostile intercept receiver than a conventional radar.

A good military intercept receiver can detect a conventional radar at a much longer range than the radar can detect the aircraft carrying the intercept receiver. This results from the added propagation loss the radar experiences since it operates over a two-way path (radar to target and target back to radar) while the intercept receiver only has to operate over a one-way path. On the other hand, the radar has the advantage of knowing what its transmitted signal is and can design its receiver as a matched filter that maximizes the output signal-to-noise ratio. The radar is basically a waveform detector that discriminates against signals that do not have the same waveform as the signal transmitted. The intercept receiver cannot depend on knowing the precise character of the radar signal it has to detect, so it is usually designed to find a radar signal based on detecting its peak-power. In order to have a low probability of its signal being intercepted, the military ubiquitous LPI radar described in this section is assumed to have its radiated energy dispersed in the three coordinates of time, frequency, and space. Hence, its peak power can be many orders of magnitude lower than that of a conventional radar of equivalent range performance. (Note that ubiquitous radars need not have their radiated energy dispersed in time and in frequency if LPI is not

important for its particular application.) In this section, an estimate is given of how much the peak power of an air-defense radar might be reduced.

Spatial domain. Here it is assumed that there are from 200 to 300 fixed receiving beams in 360 degrees of azimuth. The peak power from the broad beamwidth transmitting antenna will then be 200 to 300 times less than that of a conventional mechanically rotating air-surveillance radar, assuming coherent integration as discussed in the previous section.

Temporal domain. There are good reasons why conventional radar waveforms have a low duty cycle. Duty cycles of radars using power vacuum tubes are typically from 0.001 to 0.01. Solid-state transmitters, on the other hand, generally employ high duty cycles in order to operate efficiently. CW is preferred for solid state, but CW has disadvantages compared to pulse waveforms. As a compromise a solid-state radar might have a duty cycle from about 0.05 to 0.1. Radar designers and users have gotten used to the undesirable high duty-cycle waveforms of solid-state radars even though they require long pulses (which result in increased minimum range and increased vulnerability to certain types of deceptive countermeasures). They also require pulse compression to recover the range accuracy and resolution lost with long pulses, and multiple waveforms with different pulse widths have to be used to detect targets at the shorter ranges where targets are masked by the longer pulses. In spite of these unwelcome deficiencies, solid-state transmitters with high duty cycles have been popular. If the duty cycle of the ubiquitous LPI radar waveform is taken to be from 0.1 to 0.5, the reduction in peak power might be from 10 to 500 as compared to a conventional low duty-cycle radar.

Spectral domain. Two methods for increasing the spectral content of the radar signal, so as to reduce the radiated peak power, are spread spectrum and multiple frequencies.

Spread spectrum. This method allows the radiated signal bandwidth to be increased without having a large number of unnecessary range resolution cells with which to contend after signal processing. The signal spectrum is spread (increased) on transmit by applying either phase or frequency coding to the original signal waveform. To an outside observer (such as a hostile intercept receiver) the radiated signal appears as a wideband noise-like signal. On receive, the signal is compressed to recover the original lower-bandwidth waveform. This is similar to what is done in spread spectrum communications. If spread spectrum were to be used, the spreading of energy in the frequency domain might be from 100 to 1000, but for present purposes it might be more conservative to take the improvement to be from 50 to 300. The use of spread spectrum introduces additional complexity into the radar. Its success also depends, in part, on having waveforms with low cross correlation functions so that the waveforms from one radar do not interfere

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with the waveforms from another radar. Greater cross correlation isolation among waveforms is required with spread spectrum radar than with communication spread-spectrum systems because of the larger change in radar echo signal amplitudes (due to the R^{-4} variation of echo signal with range). As far as is known, spread spectrum has not been used in radar, so there needs to be more investigation before one can be comfortable in applying it to radar.

Multiple frequencies. In this method multiple signals at a number of different frequencies are radiated over the available radar spectral allocation.[5] At each frequency, coherent processing (or a combination of coherent and noncoherent processing) can be used to take advantage of the doppler frequency shift for detection of moving targets in stationary clutter. The processed signals from each frequency can be added noncoherently to improve the signal-to-noise ratio. If it is assumed that ten different frequencies are used, the noncoherent integration loss on adding ten such signals is about 1.7 dB, which corresponds to an effective reduction of the peak power of 8.3 dB (factor of 6.8).

There is another potential benefit in using multiple frequency transmissions, depending on the target echo characteristics. A gain in detectability can occur if the radar cross section of the target varies with frequency. The echo signals from different frequencies are assumed to be decorrelated so that a gain in detectability is obtained (similar to the gain in detectability when converting a Swerling Case 1 target model to a Swerling Case 2 model). With a probability of detection of 0.80, the theoretical improvement in signal-to-noise ratio when ten independent frequencies are used is about 4.9 dB, for a total improvement (integration plus frequency diversity) of 8.3 + 4.9 = 13.2 dB, or a factor of 21. With three different frequencies instead of ten, the improvement is 3.6 + 2.2 = 5.8 dB, a factor of 3.8. (These values are a bit "soft" since they assume that the target echo, without frequency change, is described by a Swerling Case 1 model. Not all targets are described by Swerling 1. It will also depend on the probability of detection. If the probability of detection had been 0.9 instead of 0.8, the theoretical reduction in peak power because of frequency diversity would have been 7.3 dB instead of 4.9 dB.)

We will take the reduction in radiated transmitter power because of the use of multiple frequencies to be from 4 to 20.

Sequential detection. There is another method for reducing the radiated energy without decreasing detectability, and that is the use of the technique known as sequential detection. It has not been practical previously with a conventional scanning antenna, but a ubiquitous radar that looks everywhere all the time avoids the limitations in sequential detection introduced by a scanning antenna (something first pointed out to the writer many years ago by Herman Blasbalg.)

Sequential detection is a technique well documented in the radar literature for reducing the signal-to-noise ratio required for reliable detection.[11] Instead of using a fixed number of pulses to make a detection decision, it takes advantage of the fact that many times a decision can be made as to whether a target is present or not after only a few pulses are received. Instead of using fewer pulses, a more normal number of pulses can be used with sequential detection to allow operation with a lower transmitter power (average as well as peak). When sequential detection is used with a scanning antenna beam, the beam cannot be moved to a new position until *all* of the resolution cells have made a decision. This significantly increases the time required for a decision and negates the savings offered by sequential detection. A ubiquitous radar, however, does not scan the coverage volume but stares everywhere all the time. Thus it does not suffer the limitation of a conventional phased array.

The theoretical reduction in power offered by sequential detection has been said in the early references to be about 10 dB when only noise is present and 3 dB when signal is present.[12] A more recent analysis gives the reduction in power as from 3 to 5 dB, but it is not clear that this applies to the ubiquitous radar.[13] Here it will be assumed as a compromise estimate that the potential gain from sequential detection is from 3 to 7 dB (numerical values of from 2 to 5). The gain from sequential detection is not that great compared to other methods, so it is not something that would be pursued initially unless there were some other benefits to be gained. In addition, the variable number of pulses in sequential detection will make MTI (doppler) processing difficult if it is used for detection of targets in clutter. Sequential detection, therefore, might be used only at the longer ranges where doppler processing is not required.

Long-term integration. In the previous section "Simultaneous Multiple Functions" it was indicated how the revisit time can be decreased (for a faster data rate) as the target decreases in range. Table 1 in the previous section indicated the trade-off between revisit time and range. Here we examine the reduction of the transmitter power at the longer ranges (beyond 140 nmi in our example) by the use of long-term integration. Note that it is not that the transmitted power is decreased at the longer ranges, instead it is not increased beyond the 140 nmi range. The lower echo energy from the target at longer ranges is compensated by employing a longer integration time.

Assume that only coherent integration is performed. As before, the radar is designed to achieve a 140 nmi range with a 4-s coherent integration time. With 30 s of coherent integration, Table 1 indicates such a radar can have a range of 232 nmi. If, on the other hand, a 4-s integration time rather than 30 s were desired at a range of 232 nmi, the transmitter power would have to be increased by 30/4 = 7.5. With 20 s of integration time, the range would be 209

nmi and the power five times less than a radar with a 4-s integration time. Thus it might be concluded from the above that if a longer coherent integration time is used, the transmitter power might be reduced at longer ranges by a factor of about 5 to 7.5 compared to what is required with a 4-s integration time at those ranges.

Next, consider noncoherent integration. Examination of Table 1 shows that the increase in range is not that significant when the integration time (number of pulses integrated) is increased. For example, increasing the noncoherent integration time from 20 s to 60 s increases the range by only a factor of 200/173 = 1.16. This is a small increase in range for a 3 to 1 increase in noncoherent integration time. With 20 s of noncoherent integration a range of 200 nmi can be achieved with a 1.8 (2.6 dB) increase in transmitter power, something that might be preferred over a 60 s integration time. Alternatively, with a 4-s integration time and 140 nmi range the radar power would have to be increased by a factor of 4.2 to achieve a 200 nmi range. Thus long-term noncoherent integration probably is not an attractive way to achieve LPI with a ubiquitous radar.

Coherent integration, a proper combination of coherent and noncoherent integration, or even an increase in transmitter power might be preferred instead of noncoherent long-term integration.

Track-before-detect. Another concern with long-term integration is what has been called track-before-detect, something that requires intensive signal processing. If the integration time is long enough, the target can move from one resolution cell to another, which is called "range walk." Integration of pulses has to take account of the range walk. The principle of track-before-detect was first demonstrated experimentally over 30 years ago, and the technology has improved considerably since then.[14,15,16,17] Nevertheless, it can be a challenge. The "range walk" must be accounted for, as well as changes in the target's trajectory. (The trajectory of a ballistic missile or a cruise missile might be expected to have less dramatic changes than would a fighter aircraft.)

Whether long-term integration is used at all will depend on the application and the complexity that can be tolerated. Here we shall take the reduction in transmitter power to be from 5 to 7.5 when long term coherent integration is used at long-range.

Summary of the reduction in interceptability. Table 2 summarizes the above estimates in the reduction that might be obtained in the effective power radiated by a ubiquitous radar compared to a conventional scanning high-directivity transmitting antenna beam. The summary in Table 2 provides only rough "ball park" estimates. A more accurate prediction depends on the specific design of the radar.

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The reduction in effective radiated power might vary from about 50 dB to 90 dB, depending on the assumptions. Whatever the reduction achieved in practice, one might say that a ubiquitous radar designed for LPI could have a detrimental effect on current electronic warfare (EW) intercept receivers and antiradiation missiles (ARM). All of the factors in Table 2 reduce the peak power; but the average power in this example might be reduced by about 8 to 12 dB if sequential detection and ten multiple frequencies (with enhanced cross section due to frequency diversity) are used. (This assumes a decrease of 3 to 7 dB for sequential detection and 5 dB for the use of ten frequencies that provide target cross section decorrelation.)

Table 2 ESTIMATED REDUCTION IN RADIATED POWER
compared to a conventional radar

Factor	Reduction in effective radiated peak power
Omni-transmit antenna	200 to 300
High duty cycle waveform	10 to 500
Multiple spectrum occupancy	4 to 20
Long term (coherent) integration	5 to 7.5
Sequential detection	2 to 5
Total if all are used	8×10^4 to 1.1×10^8
Spread spectrum	50 to 300
Total if spread spectrum is used instead of multiple spectrum occupancy	10^6 to 1.7×10^9

Since the ubiquitous radar is radiating everywhere all the time, the intercept receiver might attempt some degree of signal processing to enhance detectability rather than depend only on detecting the peak power of the radar signal. Although this paper has not been specific about the nature of the radar or the intercept receiver, the message of Table 2 is that there are a number of things a ubiquitous radar can provide to cause problems for electronic warfare systems whose purpose is to degrade military radar.

Other Attributes of the DBF Ubiquitous Radar

It was said earlier in this paper that a major advantage of the ubiquitous DBF radar is its ability to perform multiple functions simultaneously. It also can allow military radars to radiate a much lower peak power signal so as to make

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it more difficult for its radiated signal to be intercepted by a hostile electronic warfare system. This section presents several other advantages of digital beam-forming, most of which have been mentioned previously in the technical literature.[18,19]

No theoretical loss in signal-to-noise ratio due to nonorthogonal beams.
Since the signal-to-noise (SNR) is established at the digital output of each receiving antenna element, there is no loss in SNR when manipulating the digital outputs to form multiple beams as there is when analog beam forming is used (such as with a Butler matrix).[20] There can be any number of closely spaced receiving beams without loss in SNR. Thus digital beam-forming provides more flexibility in selecting the adjacent-beam crossover level.

Self-calibration and error correction.[19,21] Errors in phase and amplitude in the analog portion of the DBF antenna system can be compensated in the digital portion. This requires injecting a precise RF test signal at each antenna element. It has been said that the effect of mutual coupling can also be compensated in a DBF receive array.[22]

Low antenna sidelobes. The ability to digitally self-calibrate the DBF array antenna allows the potential for achieving low and ultralow receiving antenna sidelobes after digital processing.[18,19] This is especially important since the wide beamwidth of the transmitting antenna means that the two-way antenna pattern of the ubiquitous radar is about the same as the one-way pattern of its receiving antenna. Radars that operate with a one-way sidelobe pattern can experience difficulties that do not occur with radars having good two-way sidelobe patterns. However, the ability to reduce the sidelobes of the receiving array in the digital processing means that the receiving antenna can have much lower sidelobes so as to compensate, in part, for the ubiquitous radar not having two-way sidelobes.

Adaptive nulling.[19,23] Nulls can be placed in a conventional antenna's sidelobes in the direction of unwanted noise sources to keep them from entering the receiver. This is called a sidelobe canceler. Normally in a sidelobe canceler the nulls are placed with the aid of a few auxiliary low-gain antennas. This is now a well established technique. A DBF antenna, however, has the important advantage compared to a conventional sidelobe canceler of being able to place receive nulls in "beam space" by using one or more formed (directive) beams properly attenuated. This allows a null to be formed without significantly disturbing the rest of the antenna pattern (as would a conventional sidelobe canceler). This is especially important in MTI and doppler radars where undesired changes in the main-beam shape caused by a conventional sidelobe canceler can result in uncancelled clutter.

Adaptive nulling of clutter as a function of range.[18] Nulls can be formed adaptively in the antenna pattern in those directions where there are large

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clutter echoes, as well as in those directions in which there are noise sources. Unlike noise, clutter echoes are often limited in range extent. DBF allows range-dependent antenna pattern nulls to be formed only around those areas containing localized clutter or chaff, thus allowing target detection at other ranges.

Correction for failed elements.[24,25,26] The complete failure of a sufficient number of antenna elements can seriously degrade the performance of a low-sidelobe antenna. It has been said that it is possible to compensate for the loss of elements in a digital beam-forming receive array by using simple linear operations with the outputs of a small group of good elements within the array. By properly using the signals received for n elements of the array when n signals are received from different directions, it is possible, with some restrictions, to reconstruct the signal that would have appeared at the failed elements.

Conformal receiving antenna. A conformal array is one that is nonplanar, such as an array that conforms to the surface of an aircraft or a cylinder. For many years it has been a challenge using conventional array technology to provide a conformal antenna with properties approaching those of a planar array antenna. It ought to be easier to make a receiving conformal array based on a ubiquitous system since the necessary phase shifts and amplitude taper can be applied digitally. An experimental conformal array that wraps completely around the cross section of an aircraft wing has been described by Curtis et al.[27]

MTI radar. In a ubiquitous radar that performs MTI processing there is no need for the fill pulses that are used in some radar systems. Also, the antenna scan modulation that can limit the achievable MTI improvement factor of conventional radars can be reduced significantly with a ubiquitous radar because of its long observation time on a target. As mentioned previously, the longer the observation time (number of pulses available for processing) the better is the ability of an MTI doppler processor to separate moving targets from clutter. Thus the much longer time on target provided by a ubiquitous radar can provide a larger MTI improvement factor without neglecting the detection of desired targets. The large number of pulses that have to be processed in a ubiquitous antenna causes problems when long-term noncoherent integration is used (because of its large integration loss), but the large number of pulses provide many more degrees of freedom (and coherent integration without theoretical loss) from which to design doppler filters highly shaped to reject clutter and accept moving targets without excessive loss.

True time delay. A conventional phased array that can accommodate large signal bandwidths requires true time delays rather than 2π phase shifters or some form of subarray architecture. An array with digital beam-forming has

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the possibility of producing true time delays by storing the digits in a memory. This requires further examination.

Angle rate and tangential velocity. When two antennas can be widely spaced, it becomes possible to obtain a measurement of the tangential velocity just as the doppler frequency shift provides the radial velocity.[28] When both the tangential and the radial velocities are obtained, the vector velocity of the target can be found. In the ubiquitous radar, the transmitting and receiving antennas can be separated from one another. There can also be more than one transmitting antenna. Thus it is expected that a properly designed system might be able to obtain the tangential velocity as well as the radial velocity. Although there has been no real analysis of this method for obtaining the tangential velocity with a ubiquitous radar, it is an interesting concept and might be looked at further.

Burnthrough. When hostile jamming is being received in the main beam or sidelobes of the radar it can mask the desired target detection. One tactic[29] to counter jamming is to dwell for a much longer time in the suspected direction of the target (if noise is in the sidelobes) or in the direction of the noise jamming if the jammer is being carried by the target. By dwelling longer, the signal-to-noise ratio is increased and the desired target echo might "burnthrough" the noise. In conventional radars there is a serious disadvantage to burnthrough. By dwelling much longer in one direction than others, a conventional radar is not looking in the other directions that it normally has to cover. The result is a degradation in performance, even if the target masked by noise is eventually detected. Generally burnthrough is not a good defensive tactic. However, a ubiquitous radar that looks everywhere all the time does not have this limitation since increasing the integration time in one direction does not affect what occurs in other directions.

Counter-ARM. The ubiquitous concept can make a radar less vulnerable to attack by anti-radiation missiles (ARM) in several ways:
- The use of separate transmitting and receiving antennas allows the two not to be located together. Thus if the transmitting antenna is targeted by an ARM, it need not affect the receiving portion of the system located somewhere else. The transmitting antenna is much simpler than the receiving array, so that the loss of the transmitting antenna to an ARM is less of a disaster and easier to replace than the loss of the entire radar to an ARM.
- More than one transmitting antenna can be used at different locations, much like the deployment of decoy transmitters that divert an ARM. They can be designed to degrade the ARM guidance by employing a blinking strategy to confuse the ARM guidance or by introducing some type of artificial glint transmissions (similar to the countermeasure known as Cross Eye[30] that provides erroneous angle information to the attacking guidance

system and can cause it to miss its target). Multiple transmitting antennas can also reduce the vulnerability of the system to direct attack.

- If multiple frequencies are used in the ubiquitous radar, they may be radiated by more than one separate transmitting antenna. Each transmitter might radiate a series of properly timed pulses at specially chosen and changing frequencies designed to confuse the ARM guidance, as in the Counter-ARM technique invented by Irwin Olin of the Naval Research Laboratory.

Increased detectability of low cross section targets. The use of multiple frequencies and sequential detection allow the ubiquitous radar to use less average power. Previously in this paper it was said that the increase in signal-to-noise ratio (or the decrease in transmitter average power) with sequential detection might be from 2 to 5 and the decrease in average power in using 10 independent frequencies might be about 3. The two together would be an increase of from 6 to 15. When it is suspected that low observable targets have to be detected, the transmitter average power need not be reduced so as to obtain an increased echo signal. This should help in dealing with stealth. Also, one might not reduce the data rate at the shorter ranges so as to better detect low cross section targets. Thus there could be a reserve capability for dealing with low observables by employing increased power and/or increased integration time. It was mentioned previously that the longer dwell times associated with the ubiquitous radar should be of help in detecting low cross section targets in clutter by improving the doppler filtering. In any event, these are only partial measures and are not all that should be done to engage low cross section targets.

Height finding. Thus far the discussion about the ubiquitous radar has assumed a 2D system, one that provides range and azimuth angle. In the discussion earlier in the paper about multiple functions, some of the functions were not well suited for a 2D radar. For example, a 3D radar that includes the measurement of elevation angle or target height usually is needed to perform weapon control (unless the missile guidance system is sophisticated enough to work with only 2D information). There are at least three ways to obtain elevation or height with a ubiquitous radar.

One method is to have a two dimensional stack of receiving pencil beams (sometimes called a pincushion antenna), instead of a one-dimensional stack of fan beams. This greatly increases the number of outputs that require processing and it complicates the system considerably. It is something that one might not want to consider with a ubiquitous radar until there is more experience with the simpler 2D fan-beam system. If a two dimensional arrangement of pencil beams is employed, the larger aperture of the receiving array antenna (compared to a 2D radar with fan beams) covering the same volume of space allows the transmitter power to be reduced in proportion. This further improves the LPI capabilities of the ubiquitous radar.

(Depending on the nature of the radar application, the transmitter power might be lowered in this manner by a factor from about 10 to perhaps 40.)

A second approach is to employ fan beams to provide azimuth and use high-range resolution multipath height finding,[31] such as employed by the NRL Senrad experimental radar.[5] This approach requires wide bandwidth (which is always good for a military radar subject to electronic countermeasures) and is something that might be considered. The higher the radar antenna is above the surface, the less the bandwidth that is needed.

A third method is to employ a second ubiquitous fan beam receiving antenna system to provide the target's elevation angle. Such an antenna might be a vertical linear array that is phased to provide a series of contiguous conical beams of narrow beamwidth arranged as in the cross section view in Fig. 3. (When a linear array is steered in angle from broadside, the beam steers as a conical fan beam.) The number of conical fan beams need not be large, depending on the total coverage required. The first and second beams above the surface might require doppler (coherent) processing for detecting moving targets in clutter. The upper beams can perform noncoherent processing, and the higher the elevation angle the less the range required. The accuracy of elevation angle measurement and the ability to measure height accurately at low angles depends on having a narrow beamwidth. For example, a 43 ft antenna at S band ($\lambda = 0.1$ m) would produce a beamwidth of about 0.5 degree, which is a smaller beamwidth at broadside than most other height finders or 3D radar. This third approach would seem to be the technique that should be examined further.

In addition to its importance for obtaining weapon-control accuracy, there is another reason for employing a vertical array in addition to the horizontal array even for surveillance applications. Just as the vertical linear array suggested above produces a conical shaped fan beam when scanned in elevation angle, so does a horizontal linear array produce a conical shaped beam when scanning in azimuth angle. This doesn't affect detection performance (the gain doesn't decrease with scan angle as it does in a planar array) but it causes an error in azimuth angle that depends on the true elevation angle. Thus the true location of a target in azimuth cannot be found with a scanning linear array unless the target elevation angle is known. (The azimuth error is less as the vertical beamwidth is made smaller.) The inclusion of a vertical linear array allows the elevation of the target to be determined and its true location in azimuth found. It might also be mentioned that when there are a large number of targets within the radar coverage, there might be difficulty in knowing what targets found in a vertically directed conical beam are associated with what targets found in a single horizontal conical beam. An accurate measurement of the range of each target in each set of beams should help in correlating the correct angular location.
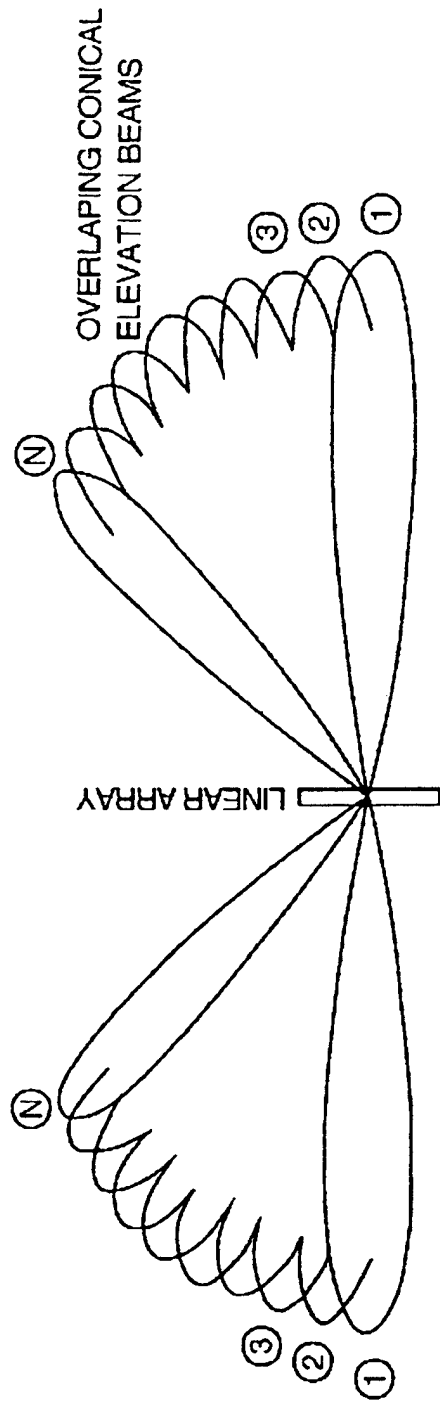
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OVERLAPING CONICAL
ELEVATION BEAMS

LINEAR ARRAY

Fig. 3 - Height finding with a ubiquitous linear receiving array producing conical beams in elevation.

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(There need not be a curved conical fan beam generated for azimuth determination if a vertical cylindrical array antenna were used to obtain the azimuth angle. Instead of beam forming in azimuth as is done in a linear array, multiple azimuth beams can be obtained by combining a different set of receiving elements of the cylindrical antenna for each direction. Each beam in azimuth is a vertical fan beam so that an accurate azimuth measurement can be obtained.)

Relation to active aperture phased arrays. The concept of an active aperture array has been popular in recent years. One reason is that it avoids the losses usually found in the constrained, or corporate, feed systems employed with some phased arrays. Active aperture radars, however, are currently of high cost, and it is not obvious that they are the proper choice of system architecture for all radar applications requiring a phased array. The ubiquitous radar need not employ a constrained feed on transmit and thus does not have this loss. On receive, it resembles an active aperture in that there is a receiver at each element so that the noise figure of the system is established before major losses occur, and there are no analog phase shifters or traditional duplexers employed as in the active aperture. Thus the ubiquitous radar has many of the same advantages offered by the active aperture. The active aperture array, on the other hand, does not have the important advantages of a ubiquitous radar for performing multiple simultaneous functions and providing LPI.

Some Equipment Considerations

Digital signal processing. The heart of a ubiquitous radar is its digital beam forming and digital signal processing. The ubiquitous radar will make serious demands on digital processing, but it offers advantages not available with other radar architectures. One has to be careful, however, to have the necessary dynamic range and capable A/D converters. However, the integration of a large number of pulses that is a characteristic of a ubiquitous radar can ease the dynamic range problem. The desire to operate over a wide bandwidth will also tax the processing and other components of the system. This radar utilizes long-term integration of the received echo signals, something with which there has not been much previous experience. The proper balance between coherent and noncoherent integration has to be determined. Coherent integration does not have the theoretical loss that noncoherent integration has, but it is more difficult to implement.

Transmitters. As mentioned previously, the use of wide bandwidth and a high duty cycle are not essential elements of a ubiquitous radar unless a low probability of intercept is desired. When these characteristics are required the RF power sources can be solid state transistors, traveling wave tubes, or the microwave power module (MPM) which is a combination of solid state and

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TWT. These RF power sources are more suited for wideband, high duty cycle operation than they are for a conventional radar architecture.

Transmitting antenna. The transmitting antenna is simpler than for other radar architectures. It is nonscanning and is of smaller size since it radiates uniformly over a large angular region. The use of separate transmitting and receiving antennas reduces the duplexer problem. Assuming the large receiving antenna cannot be elevated in height but the small transmitting antenna can, there might be only a one-way (target to the low-sited receiver) diffraction loss rather than the two-way diffraction loss of a conventional low-sited radar antenna. Because the transmitting antenna can be relatively small there might be more than one of them so as to attempt to degrade ARM guidance as mentioned earlier. If multiple frequencies are used, they may be radiated by separate transmitting antennas or by a single antenna.

Other. Early efforts to explore the implementation of digital beam forming for radar systems can be found in Steyskal and Rose[21] and in Farina.[32]

Potential Military Applications

Air defense. Much of the previous discussion in this report related to the air-defense application. In addition to having a considerably reduced radiated peak power that lowers the probability of intercept, the ubiquitous radar can simultaneously search at long ranges with a low data rate, search at a higher data rate for low-altitude targets that pop-up at short range, control weapons to an intercept with a high data rate, acquire targets at any range much faster, and perform burnthrough and/or noncooperative target recognition with a long duration observation.

Some air defense systems that employ multifunction phased array radars have only modest doppler processing because of the limited time they can dwell in any particular direction. Therefore, they can have difficulty in detecting moving targets in land or weather clutter. This can be a very serious limitation to military air defense. The reason for this lack of doppler capability is that good doppler processing requires a long time-on-target (or dwell time). As mentioned previously, a multifunction phased array radar for air defense does not always have the luxury of a long time-on-target because its many functions are time shared. An important advantage of a ubiquitous radar is that it can have a much longer time-on-target since its many functions are accomplished in parallel rather than one at a time.

HF over-the-horizon (OTH) radar. The U. S. Navy ROTHR[33] (relocatable over-the-horizon radar), developed in the late 1980s, already employs digital beam forming. It has 16 contiguous receiving beams covering a wide sector in azimuth and a wide-beam transmitting antenna covering the same angular

sector. This was an early application of DBF. Digital beam forming is easier to accomplish at HF than at microwave frequencies since HF OTH radar has much narrower signal bandwidths than does a microwave radar. ROTHR, however, cannot perform simultaneous multiple functions since its sixteen receiving beams and the single transmitting beam are stepped together in azimuth over eight sectors to provide 60 degrees of azimuth coverage. It should be relatively straight forward to now increase the number of receiving beams to include its entire coverage area.

An HF OTH radar can detect aircraft, ships, ballistic missiles, and can provide the wind speed and direction over the ocean. Each of these requires a different dwell time and a different revisit time. For example, an OTH radar has to dwell for about one to three seconds to detect aircraft. The revisit time is from 10 to 20 s. Ship detection requires long dwell times of from several tens of seconds to about two minutes, but the revisit time can be one hour. Thus a conventional OTH radar that detects ships cannot simultaneously detect aircraft. An HF OTH ubiquitous radar, on the other hand, can simultaneously detect aircraft, ships, and ballistic missiles, and ocean winds. It might be noted that HF OTH radar can readily recognize helicopter targets by the harmonics introduced by the blade frequency, an important need for observing the battlefield. Ships have large radar echoes at HF, but they are of slow speed so their doppler shifted echo can be close to the doppler shifted echo from the moving sea. OTH radars for the detection of ships therefore require large antennas (over a mile long in some current OTH radars) in order to reduce the amount of sea clutter with which the target must complete. The long time of observation possible with a ubiquitous radar (since ships do not change course as rapidly as do aircraft) can result in narrow doppler filters, which might reduce the need for a large antenna. Likewise a cruise missile is less likely to perform maneuvers than a manned aircraft so its detection might be enhanced by the long-term integration offered by a ubiquitous radar.

The HF OTH radar is a good candidate for a ubiquitous radar. The required technology is easier to achieve than at microwaves, there are multiple functions that would benefit from simultaneous operation, and the current OTH radars already have digital beam forming.

Battlefield radar. Here it is assumed that the radar is on the ground. The multiple functions that might be performed by a single ubiquitous battlefield radar include:
- Short range air surveillance and engagement of fixed-wing aircraft, helos, and battlefield UAVs.
- NCTR of helicopters based on blade signature.
- Mortar and artillery detection location, and direction of counter-fire.
- Personnel and ground vehicle surveillance.

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- Moderate range air surveillance to obtain the "air picture" needed for situational awareness and air-traffic control.

The first four of the above are generally of short range and might be obtained with one ubiquitous radar mounted on HMMWVs. It is not now obvious that general air surveillance (the fifth function listed above) should be included with the other four, or whether a separate longer range radar would be better.

Airborne air-surveillance (AEW and AWACS). The chief benefit of a ubiquitous radar for airborne air-surveillance is low probability of intercept. (This assumes a wide operational bandwidth and a high duty cycle waveform.) Since these radars perform important military missions it should be expected that a determined adversary would want to negate their effectiveness. An ARM designed for such radars should be expected. Thus the benefits offered by a ubiquitous radar for low probability of intercept ought to be of value for this application.

Airborne missile warning. LPI would be the chief reason for employing the ubiquitous concept.

Two Potential Civil Applications

Air-traffic control. Currently the FAA airport surveillance radars (ASR) are designed to detect and track aircraft in the vicinity of airports and to indicate the regions where rainfall is occurring. A separate radar called the Terminal Doppler Weather Radar, or TDWR, is located in the vicinity of an airport to warn of the hazardous downburst, or wind shear. A few years ago the FAA conducted a study known as TASS (Terminal Air Surveillance System) to determine how to accomplish the functions of these two radars in a single system. The ubiquitous radar was not considered at that time and the proposed solutions were generally two radars combined with back-to-back antennas.[34] It would seem that a single ubiquitous radar might be able to perform the functions of aircraft detection, weather observation, and detection of the downburst. It might also be able to detect and recognize hazardous bird concentrations in the vicinity of the airport, something not easily done with current airport surveillance radars.

Weather radar. The Nexrad doppler weather radar might also benefit in applying the ubiquitous radar concept to perform multiple observations simultaneously. The Nexrad does a fine job of observing the weather but it takes about 5 to 10 minutes to complete an observation (or revisit time). The long revisit time is due to its one degree pencil that has to observe 360 degrees in azimuth by about 20 degrees in elevation. In addition, a relatively long dwell time is needed at each observation, not just for enhancing the detection

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of signal in noise, but for producing a good average value of the highly fluctuating weather echo.

Closing Comments

The ubiquitous radar considered in this paper employs a quite different radar architecture than is currently found in radar systems. It offers many attractive new capabilities. Some of the features of the digital beam-forming radar have been described previously in the literature or even verified experimentally under limited conditions, but nothing similar to what has been discussed here for its extension to a ubiquitous radar has been fully considered or demonstrated experimentally. There are, however, some highly challenging technical issues associated with such a radar. These include achieving the necessary digital signal processing, handling long-duration coherent integration, employing the proper combination of coherent and noncoherent integration, operating with an omni-transmitting antenna and highly directive receiving antennas, and simultaneously achieving multiple radar functions with a single radar. By employing waveforms with high duty cycles and operating at multiple frequencies within a relatively wide frequency spectrum, the ubiquitous radar can provide a far greater degree of LPI performance than heretofore practical. It remains to apply these concepts to enhancing the capability of important radar applications.

In summary, the two major advantages offered by the type of ubiquitous radar discussed here are (1) simultaneous multiple radar functions and (2) low probability of intercept. If neither of these are of importance in a particular radar application than the ubiquitous radar has less to offer and other architectures might be considered. Other advantages that accrue from the use of the ubiquitous architecture (which can include high duty-cycle waveforms and operation over a wide spectral region) include the following:
- better shaping of doppler filters because of the large number of pulses available
- multiple frequencies to resolve ambiguities
- low sidelobes
- rapid target acquisition
- longer observation times as needed for NCTR
- burnthrough without taking time away from other functions
- low loss, similar to that of an active aperture
- counter ARM
- potential for counter stealth, conformal antenna, sequential detection, true time delay

Although a lot has been indicated here about the ubiquitous radar, there is much more that needs to be explored. The next step should be a conceptual design for a particular radar application. The HF over-the-horizon radar,

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multifunction air-traffic control radar, and military air defense seem to be the most attractive applications to consider. There are many challenges, but the end result can be the achieving of a new method for operating a phased array radar to obtain significant capabilities not practical otherwise.

Appendix I - Past DBF Efforts

There have been several operational radar systems that employ DBF and several theoretical analyses and laboratory experimental demonstrations of special capabilities available with DBF that are hard to duplicate with conventional radar systems. Some of these have been cited as references in this paper. The work with which this author is aware is summarized below. These are examples of digital beam forming, and not its application as a ubiquitous radar as described in this paper.

- *SMART radar.*[35] This is a 3D S-band air-surveillance radar developed in the mid-1980s by Signaal (Netherlands). It has 12 fixed elevation beams which are generated from 16 antenna elements by use of DBF. The L-band version, which came later, generates 14 beams.

- *Relocatable Over-the-Horizon Radar (ROTHR), AN/TPS-71.* This radar was developed by Raytheon for the U. S. Navy. It uses DBF to generate 16 independent beams from a linear array of 372 pairs of antenna elements. Its development took place in the mid-1980s. The U. S. Air Force AN/FPS-118 OTH radar, developed in the early 1980s, employs an antenna with fewer elements and has five simultaneous beams.

- *U. S. Air Force Rome Laboratories, Hanscom AFB, MA.* Hans Steyskal and his colleagues have examined much of the basic aspects of DBF radar systems, as evidenced by their several informative publications.[21,25,36,37]

- *Standard Telecommunications Laboratory, England.* The paper by P. Barton[18] was one of the first to describe the many advantages of DBF radar. The technology of that time (late 1970s) did not permit the type of radar system discussed in this paper.

- *FGAN-FFM, Germany.* Papers by W. D. Wirth[38,39] describe the benefits of multiple beam radar, including the application of sequential detection and signal integration.

- *Japanese interests.* The use of digital beam-forming for mobile communications has been reported by a group of four authors from four different Japanese organizations.[40] An experimental communications system with 16 digitally formed beams demonstrated the feasibility of DBF to adaptively track communication signals from satellites and to adaptively reject unwanted signals, including those that arrive via multipath propagation. It was reported in this paper that "progress in digital device technologies is making DBF antennas a possibility for commercial communication." The Japanese company Toshiba

Corporation has also described their work on key technologies for use with DBF in radar applications.[41]

- *Swedish Defense Research Establishment.*[42] An experimental 12-beam S-band digital beam-forming antenna was designed and demonstrated for radar applications.

- *Thomson-CSF, France.*[43] This is an experimental C-band radar for battle-field air surveillance that generates 16 simultaneous receive beams in conjunction with a broad-beam transmitting antenna. It demonstrated adaptive jammer suppression and recognition of helicopters based on their blade flash. It was said that future interests were for battlefield surveillance of ground targets.

- *East China Research Institute of Electronic Engineering.*[44] This work was concerned with an eight-element DBF array in which a directive transmitting beam was generated by digital beam forming, as was the receiving array. A null was placed in the transmitting beam. (In the present report, the transmitting array was always assumed to have a broad beamwidth. A directive transmitting beam, as in the Chinese paper, does not allow the advantages of a ubiquitous radar to be obtained.)

The above indicate that there has been quite a bit of foreign interest in this subject, not all of it for radar applications.

Appendix II - Past Efforts in Analog Beam Forming

In the late 1950s and early 1960s there was interest in forming multiple simultaneous beams from a phased array by employing analog methods, which means lots of "hardware." This occurred before the rapid advances in digital technology that began in the 1970s. Analog beam forming was quite limited compared to what is believed to be possible with modern digital methods. The beam-forming system concepts at that time were mostly based on linear array antennas that provided multiple beams in only one angular coordinate since the implementation in two angular coordinates was far too cumbersome. Also, long-term integration was not practical at that time since only analog processing methods were available. Nevertheless, the technology and the concepts for analog beam forming were new (for its time) and different, and there was considerable attention paid to this subject.[45]

When it was realized that analog beam forming had many serious practical limitations (mainly due to the bulky hardware and lack of long-term integration), interest waned. Thus there is no need to go into detail. Instead, this appendix will briefly list some of the efforts that were conducted 30 to 45 years ago as an indication of the historical basis for beam-forming radar. Mentioned are two radars that employed early analog beam-forming methods: one for aircraft height finding, the other for ballistic missile defense. The interest was mainly for receiving arrays.

The postamplification beam-forming array, PABFA, is an N-element beam-forming array with M phase shifters attached in parallel to each element of the array, for a total of NM phase shifters. These phase shifters are then combined from element to element so as to obtain M beams that look in different directions. It is a "brute force" way to obtain the M beams of a beam-forming array. This type of array can become rather cumbersome when the number of beams is large. A slight simplification is had when each element has a tapped delay line that operates at IF. The outputs of the taps on the various IF delay lines are combined to form M beams each looking in a different direction. The role of the IF delay lines, or the role of the RF delay lines mentioned next, may be hard to visualize without a diagram, but they can be found in the ancient literature on this subject or in the first or second editions of *Introduction to Radar Systems*.

The M multiple beams can also be generated with tapped RF waveguides attached to each element of the array. A one-of-a-kind developmental radar employing RF beamforming was the FAA's AHSR-1 height finder at S band.[46] The AHSR-1 was a receive-only system that received the transmitted signals of the conventional rotating fan-beam airport surveillance radar. Each waveguide had a series of directional couplers along the waveguides to tap off a portion of the received signal at the proper intervals. The outputs of the 160

ft high antenna were combined to form 111 beams in elevation in each of three faces in order to determine the height of aircraft for purposes of air-traffic control. A total of 30 miles of S-band waveguide were used to form the beams. The radar was built and tested, but there was no further interest.

The mathematical basis of the RF (microwave) beam former in the previous paragraph is the conventional Fourier transform. The microwave analogy of the Fast Fourier Transform (FFT) is the Butler beam-forming matrix. Just as the FFT is a considerably simplified way to perform a Fourier transform, so the Butler matrix is a much simpler method for producing multiple analog beams than is the RF beam forming of the previous paragraph. Although the Butler matrix simplified the hardware required for beam forming, it still was cumbersome. Experimental models of the Butler matrix were built, but to the writer's knowledge, it never was used in an operational radar for forming multiple parallel beams.

The Luneburg lens is a spherical lens constructed of concentric layers whose dielectric constant varies with the radius of the sphere. A plane-wave incident on its surface is focused to a point on the surface diametrically opposite.[47] Because of its spherical symmetry, a series of beams in elevation can be obtained by placing contiguous receiving horns along a portion of a vertical circumference of a great circle of the Luneburg lens. The radars for the Nike Zeus AICBM (anti-intercontinental ballistic missile) defense system used such an antenna (in the 1950s, before electronically steered phased arrays were practical).[48] The 120 ft diameter Luneburg lens (actually a hemisphere was used instead of a sphere) of the Nike Zeus system generated 60 one by one degree pencil beams that were mechanically rotated as a group to cover the desired surveillance sector. The Nike Zeus, an exoatmospheric engagement system, was changed to the Nike-X endoatmospheric engagement system when it was realized that exoatmospheric engagement was not likely to succeed if the attacker employed penetration aids. The change in system concept allowed the Nike-X to change to the newly developed phased array technology rather than the Luneburg lens antenna.

The purpose of including this brief appendix was to indicate the limitations of analog beam forming hardware in spite of efforts to employ them in operational systems. These limitations can be overcome with the use of digital beam forming and digital signal processing.

Appendix III - Relation Between the Azimuth Pointing Angle of the Antenna Beam and the True Target Azimuth Angle in a Scanning Linear Array Antenna

In the subsection *Height finding* that appears in the Section "Other Attributes of the DBF Ubiquitous Radar" it is said that when a horizontal linear array antenna is scanned from the broadside direction, the azimuth pointing of the direction of the beam is not the true azimuth direction of the target if the target is not at zero degrees elevation. This results because the beam does not maintain a planar shape when scanned in azimuth, but scans as a cone. Thus the beam is curved in elevation. The greater the scan angle the greater is the curvature and the larger is the azimuth shift. The target height, or elevation angle, has to be determined in order to find the true azimuth of the target. The purpose of this appendix is to obtain a relationship between the antenna azimuth pointing angle θ (measured at zero degrees elevation), the target elevation angle ϕ, and the true target azimuth $\theta + \Delta\theta$.

The geometry of the beam is shown in Fig. III-1 (a). The antenna is steered to an angle θ in the horizontal plane as measured from the broadside direction (the x-axis) of the linear antenna lying along the y-axis and centered at the origin O. When the beam is steered an angle θ from the x-axis it is also steered an angle θ from the vertical z-axis, as shown in the figure. A target at a range R will lie on a circle of radius $r = R \cos \theta$, as indicated in (b) and by the heavy curved line in (a). From (b) it is seen that the height h of the target is given by $h = R \sin \phi$, where ϕ is the elevation angle. We will need the length l, which because of the right triangle in (c) is $(r^2 - h^2)^{1/2}$. The shift in azimuth angle $\Delta\theta$ shown in (a) and in (c) is $\Delta\theta = \pi/2 - \theta - \alpha$. From Fig. III-1 (d) it is seen that $\sin \alpha = l/(R \cos \phi)$, so that

$$\alpha = \arcsin [(r^2 - h^2)^{1/2}/(R \cos \phi)] = \arcsin [(\cos^2 \theta - \sin^2 \phi)^{1/2}/\cos \theta]$$

Then the shift in azimuth angle is then

$$\Delta\theta = \pi/2 - \theta - \arcsin [(\cos^2 \theta - \sin^2 \phi)^{1/2}/\cos \theta] \qquad (1)$$

A plot of this equation is shown in Fig. III-2. The shift in the apparent target azimuth can be significant. It is seen that a correction in $\Delta\theta$ is needed when the beam is steered in azimuth beyond 5 or 10 degrees and the target elevation angle is more than 5 or 10 degrees.

It should be mentioned that the above applies for a linear array. Most linear antennas for this application would likely have some vertical aperture. In the
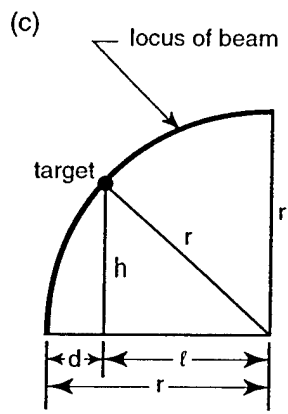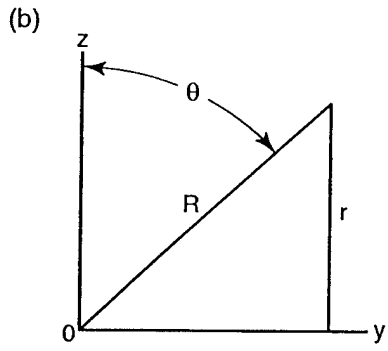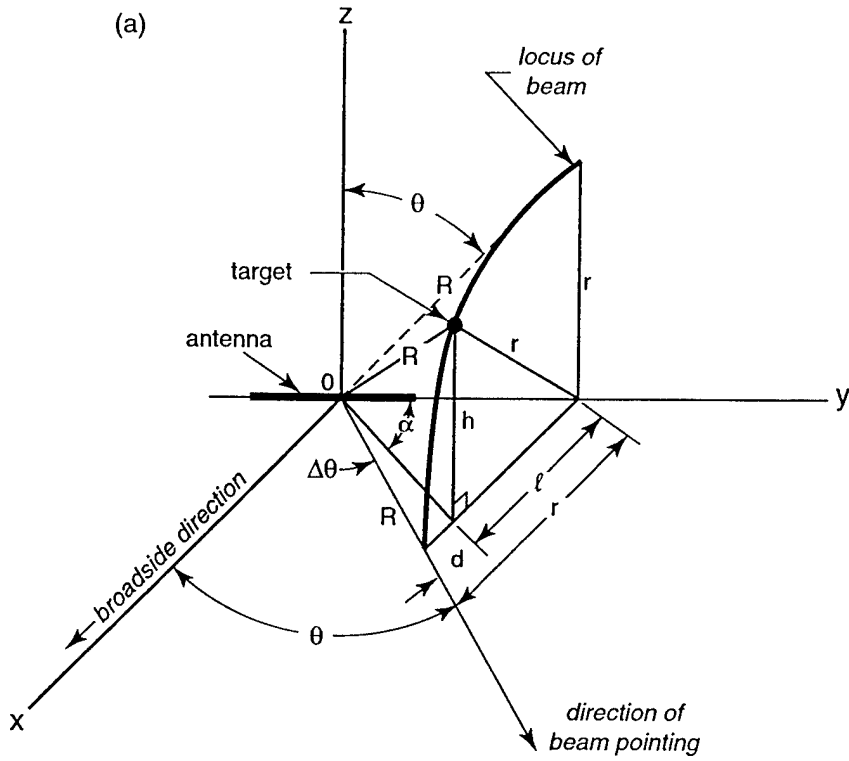
33

Fig. III-1(a) — Geometry of scanning a beam in azimuth with a linear array antenna. (b) Cut in the y-z plane. (c) Cut in the target plane.
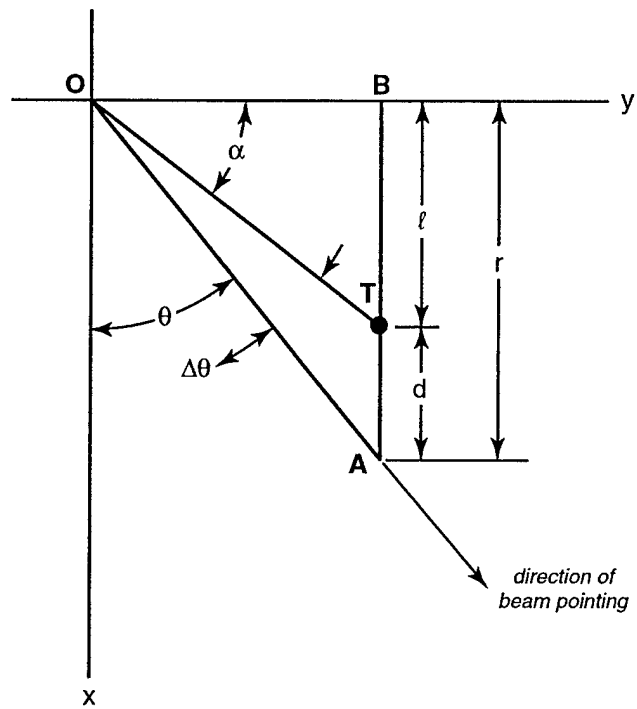
Fig. III-1(d) — Geometry in the horizontal x-y plane. "T" is projection of the target position in the horizontal plane. OA = R = range. OT = R sin ϕ, where ϕ = elevation angle, and OB = R cos θ.
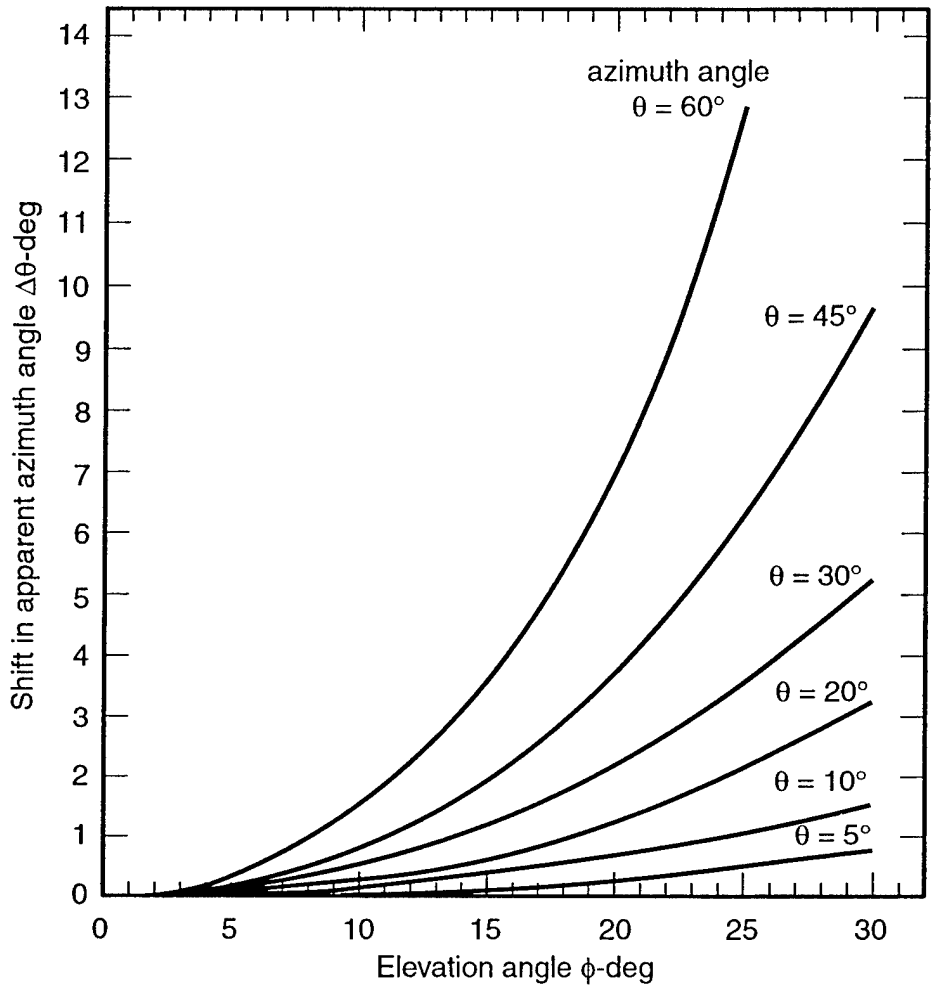
Fig. III-2 — Plot of the shift $\Delta\theta$ in the azimuth angle when a linear antenna is scanned in azimuth θ and the target is at an elevation angle ϕ.

example of Fig. III-2 where the antenna is scanned to no more than 30 degrees in elevation, the vertical aperture would be about two wavelengths. Although an analysis has not been conducted, it would seem that the larger the vertical aperture the less the effect of the change in vertical beam shape.

Originally a different equation for the shift in azimuth angle $\Delta\theta$ was derived in a different manner. It found the distance d in Fig. III-1(c) in terms of r and l, and solved for the angle $\Delta\theta$ using the law of cosines. It gave the following :

$$\cos\left(\Delta\theta\right) = \frac{\sin^2\theta + \cos\theta\left(\cos^2\theta - \sin^2\phi\right)^{1/2}}{\cos\phi} \tag{2}$$

This equation was found to require far more accuracy than does Eq. (1) when the angle $\Delta\theta$ is small. Below one degree, five or more significant figures seem to be required. Eq. (1) does not have that problem, and so is preferred.

The vertical pattern of a circular or a cylindrical array antenna need not change its shape when scanned in azimuth, and would not have the problem mentioned in this appendix.

References

1. Patton, W. T., "Compact, Constrained Feed Phased Array for AN/SPY-1," in *Practical Phased-Array Antenna Systems,* E. Brookner (ed.), Lecture 8, Artech House, Bostyon, 1991.
2. Carey, D. E. and W. Evans, "The Patriot Radar in Tactical Air Defense," *IEEE EASCON Record,* pp. 64-70, 1981. Also printed in *Radar Applications,* M. Skolnik (ed.), pp. 185-191, IEEE Press, N. Y. 1988.
3. Baugh, Richard A., *Computer Control of Modern Radars,* Published by RCA Missile and Surface Radar Division, Moorestown, N. J., 1973.
4. Skolnik, M., "Improvements to Air-Surveillance Radar," *Proc. of the 1999 IEEE Radar Conference,* Waltham, MA, April 20-22, 1999, pp. 18-21.
5. Skolnik, M., G. Linde, and K. Meads, "Senrad: An Advanced Air-Surveillance Radar," *IEEE Trans.,* vol. AES-37, pp. 1163-1175, October, 2001.
6. Kerr, D., S. Mussman, and C. Bachmann, "Automatic Recognition of ISAR Ship Images," *IEEE Trans.,* vol. AES-32, pp. 1392-1404, October, 1996.
7. Bell, M. R., and R. A. Grubbs, "JEM Modeling and Measurement for Radar Target Identification," *IEEE Trans.,* vol. AES-29, pp. 73-87, January, 1993.
8. Wirth, W. D., "Long Term Integration for a Floodlight Radar, *1995 IEEE International Radar Conference,* pp. 698-703.
9. Collot, G., "Fixed/Rotary Wings Classification/Recognition," *Proc. of the CIE International Conference on Radar,* Beijing, Chnia, Oct. 22-24, 1991, pp. 610-612.
10. Bullard, B. D, and P. C. Dowdy, "Pulse Doppler Signature of a Rotary-Wing Aircraft," *Proc. 1991 IEEE National Radar Conference,* Los Angeles, CA, March 12-13, 1991, pp. 160-163.
11. Skolnik, M., *Introduction to Radar Systems,* 3d edition, McGraw-Hill Co., New York, 2001, pp. 286-287.
12. Preston, G. W.: "The Search Efficiency of the Probability Ratio Sequential Search Radar," *IRE Intern. Conv. Record,* vol. 8, pt 4, pp. 116-124, 1960.
13. Wirth, W. D., "Sequential Detection for Energy Saving and Management," *1996 IEEE Phased Array Conference,* Boston, MA, pp. 289-292.
14. Prengaman, R. J., R. E. Thurber, and W. G. Bath, "A Retrospective Detection Algorithm for Extraction of Weak Targets in Clutter and Interference Environments," *IEEE Eascon 83,* Washington, D. C., Sept 19-21, 1983, pp. 153-157.
15. Allen, M. R., S. L. Katz, and H. Urkowitz, "Geometric Aspects of Long-Term Noncoherent Integration," *IEEE Trans.,* vol. AES- 25, pp. 689-700, September, 1983.
16. Perlovsky, L. I., "MLANS Neural Network for Track Before Detect," *IEEE 1993 National Aerospace and Electronics Conference,* Dayton, OH, May 24-28, 1993, pp. 377-382.
17. Elazar, M., "Search Radar Track-Before-Detect Using the Hough Transform," Master's Thesis, Naval Postgraduate School, Monterey, CA, March, 1995.
18. Barton, P., "Digital Beam Forming for Radar," *IEE Proc.,* vol. 127, Part F, No. 4, August, 1980.
19. Steyskal, H., "Digital Beam Forming Antennas, An Introduction," *Microwave J.,* vol. 30, pp. 107ff, January, 1987.
20. White, W. D., "Pattern Limitations in Multiple-Beam Antennas," *IEEE Trans.,* vol. AP-10, pp. 430-436, July, 1962.
21. Steyskal, H., and J. F. Rose, "Digital Beam Forming Systems for Radar Systems," *Microwave J.,* vol. 32, pp. 121ff, Januarly, 1989.
22. Steyskal, H. and J. S. Herd, "Mutual Coupling Compensation in Small Array Antennas," *IEEE Trans.,* vol. AP-38, pp. 1971-1975, December, 1990.
23. Brookner, E., and J. M. Howell, "Adaptive-Adaptive Array Processing," *Proc. IEEE,* vol. 74, pp. 602-604, April, 1986.
24. Weber, M. E. and R. Heisler, "A Frequency-Domain Beamforming Algorithm for Wideband, Coherent Signal Processing," *J. Acoust. Soc. Am.,* vol. 76, no. 4, pp. 1132-1144, October, 1984.

25. Steyskal, H.: "Digital Beamforming at Rome Laboratory," *Microwave J.,* vol. 39, pp. 100ff, February, 1996.

26. Mailloux, R. J.: "Array Failure Correction with a Digitally Beamformed Array," *IEEE Trans.,* vol. AP-44, pp. 1543-1550, December, 1996.

27. Curtis, D. et al., "Conformal Array Control using Digital Beamforming," *2001 Antenna Applications Symposium,* Allerton park, Monticello, IL, pp. 336-363, October 30 and 31, 2001.

28. Skolnik, M., "Radar Information from the Partial Derivatives of the Echo Signal Phase from a Point Scatterer," *Naval Research Laboratory, Washington D. C.,* Memorandum Report 6148, February 17, 1988.

29. Van Brunt, L.B., *Applied ECM, Vol. 2,* EW Engineering, Inc., Dunn Loring, VA, 1982, pp. 113-119.

30. Lewis, B. L. and D. D. Howard, "Security Device," U. S. Patent 4,006,478, Feb. 1, 1977.

31. Skolnik, M., *Intoduction to Radar Systems,* 2d ed., McGraw-Hill Book Co., New York, 1980, pp. 546-0547.

32. A. Farina, *Antenna-Based Signal Processing Techniques for Radar Systems,* Artech House, Boston, 1992, Sec. 2.7, "Digital Beam-Forming (DBF) Technique."

33. Headrick, J. M. and J. F. Thomason, "Naval Applications of High Frequency Over-the-Horizon Radar," *Naval Engineers Journal,* vol.108, N0. 3, pp. 353-362, May, 1996.

34. Buckler, L., "Dual-USE Air Traffic Control Radar," *1998 IEEE National Radar Conference,* Dallas, TX, 12-13 May 1998, pp. 26-31.

35. Taken from brochures of the Hollandse Signaalapparaten B. V.

36. Steyskal, H., "Digital Beamforming at Rome Laboratory," *Microwave J.,* vol. 39, pp. 100ff, February, 1996.

37. Steyskal, H. : Digital Beam Forming Antennas, An Introduction, *Microwave J.,* vol. 30, pp. 107ff, January, 1987.

38. Wirth, W. D.: Long-Term Integration for a Floodlight Radar, *1995 IEEE International Radar Conference,* Washington, D. C., pp. 698-703.

39. Wirth, W. D.: Energy Saving by Coherent Sequential Detection of Radar Signals with Unknown Doppler Shift, *IEE Proc.,* vol. 142, Pt. F, pp. 145-152, June, 1995.

40. Chiba, I., R. Miura, T. Tanaka, and Y. Karasawa: Digital Beam Forming (DBF) Antenna System for Mobile Communications, *IEEE AES Systems Magazine,* pp. 31-41, September, 1997.

41 Miyauchi, H. et al.: Development of DBF Radars, *1996 IEEE International Symposium on Phased Array Systems and Technology,* Boston, MA, 15-18 October, 1996, pp. 226-230.

42. Pettersson, L., M. Danestig, and U. Sjostrom: An Experimental S-band Digital Beamforming Antenna, *IEEE AES Systems Magazine,* pp. 19-26, November, 1997.

43. Larvor, J. P., et al.: SAFRAN: a Digital Beamforming Radar for Battlefield Applications, *Radar 97, 14-16 October, 1997, IEE Publication No. 449,* pp. 60-64.

44. Yan, W., W. Manqing, J. Xueming, and L. Jaiguo, "The Development of DBF Phased Array Radar System," *2001 CIE International Conference Radar Proceedings,* Oct. 15-18, 2001, Beijing, China, pp. 61-64.

45. Ricardi, L. J., "Array Beam-Forming Networks," *MIT Lincoln Laboratory Technical Note* 1965-12, 13 April 1965.

46. Blass, J., "Multidirectional Antenna - A New Approach to Stacked Beams," *1960 IRE International Convention Record,* vol.1, pp. 48-50.

47. Skolnik, M., see ref. 31, pp. 252-253.

48. Fagen, M. D. (ed,), *A History of Engineering and Science in the Bell System,* vol. 2, Bell Telephone Laboratories, Inc., 1978, p. 402.