POTENTIAL ENHANCEMENTS TO THE PERFORMANCE OF ASDE RADARS DERIVED FROM MULTISTATIC RADAR PRINCIPLES

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Introduction

Airport surface surveillance systems, such as Airport Surface Detection Equipment (ASDE) radars, are susceptible to multipath propagation and scattering effects that can result in the placement of false targets located at critical locations on airport surfaces such as runways and taxiways [1]. Such false targets can readily compromise the performance of these radars and lead to highly undesirable controller reactions, including unnecessarily aborting landing and takeoff operations when such multipath false targets are located on runways. These situations affect the efficiency of operations and also reduce user confidence in ASDE radar and related systems, thereby adversely affect safety. Evaluation of this problem led to consideration of enhancing ASDE radar performance by transforming the current monostatic radar to a multistatic configuration (ASDE-MP). Multistatic radar provides for multiple detection of targets as well as significant differential responses to the multipath scattering phenomenon responsible for false target detection. The latter property diminishes the detection of false targets by combining information from a number of radar receivers, positioned at different locations to provide surveillance over common areas of interest on the airport surface.

This paper examines a set of major principles associated with the multistatic radar concept as applied to the ASDE-3[1] radar system. The principles include: system architecture; geometrical considerations; dependence of system performance on the number of multistatic receivers; radar cross-section behavior; antenna requirements; surface and rainfall clutter effects; bistatic gain; resolution cell size; time synchronization; and polarimetry. The overarching result is that the concept appears feasible and deserving of further consideration as an effective means of improving the performance of ASDE surveillance radars.

Characteristic False Target Scenario

The ability of the ASDE-3 radar and associated tracking and automated alerting systems, such as the Airport Movement Area Safety System[2] (AMASS), is often significantly compromised by the presence of false targets produced by multipath propagation and scattering effects. The generation of these false targets is exacerbated by the physical complexity of the airport environment, which often leads to the appearance and persistence of such targets in critical areas of airport movement areas. These conditions can lead to false alerts being issued by AMASS or other similar tracking systems that depend on ASDE radars for surveillance of the airport surface. Several multipath mitigation algorithms have been developed to improve this situation, but these remain subject to error and can add three or more seconds to the ASDE-3/AMASS safety assessment and alerting process.

Multipath false targets can be generated in several ways. Generally, the process involves scattering of radar energy from several targets located along multiple propagation paths. The most common multipath situation is illustrated in Fig. 1. The radar return consists of the time-differentiated combination of two scattered waves returned along the same primary path from a real target located along the main beam of the radar. The first return signal represents scattering from the real target. The second return derives from bistatic scattering from

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[1] The ASDE-3 is an advanced digital radar that penetrates rain, snow and fog to superimpose radar images of all moving airplanes and vehicles over a map of the airport surface.

[2] AMASS uses data from the ASDE-3 to determine conflicts based on the position, velocity and acceleration of airborne arrival aircraft with ground-based aircraft and vehicles. It provides air traffic controllers with visual and aural alerts of potential runway accidents caused by runway incursions.

the same real target to a secondary scatterer that monostatically returns energy back to the real target for reciprocal bistatic return to the radar. The secondary scatterers (e.g., aircraft, ground vehicles, building, etc.) have large enough radar cross-sections for the scattered energy back to the radar to be detected and interpreted as a real target. The two-path delay of the secondary signal causes the radar to interpret it as arising from a target located along the main beam at a distance from the real target equal to the distance from the real target to the secondary scatterer.

Another multipath source of interference that can arise from this arrangement (not shown in Fig. 1) is the situation where the radar energy incident on the secondary target is bistatically scattered directly (or possibly indirectly via propagation and additional scatter and propagation to and from other scatterers) back to the radar for possible detection through the sidelobes. In this instance, a false target could possibly appear at a location between the real target and the false target shown in the figure.

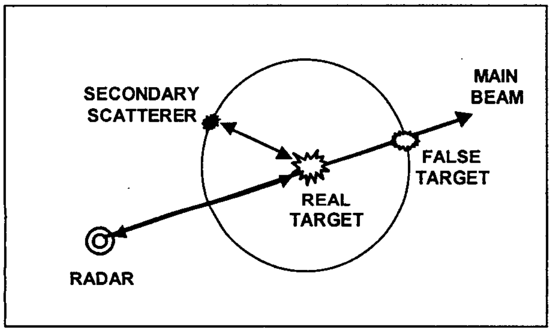

Fig. 1. Typical Geometry Responsible for Generating Multipath False Targets.

The type of multipath described above differs from the classical multipath situation. The latter typically applies to the case where targets in the near-ground environment receive radar energy along two separate paths -one directly from the radar and the other indirectly from the radar via reflection from the ground. This situation can produce radar returns that are the sum of the two scattered waves returned along the two paths to the same target. The effect can be either an increase or decrease in the total radar signal from the real target due to constructive or destructive interference, respectively, of the two received signals. Although this phenomenon is present in ASDE radars, its effects are not of major importance because of the complex nature of surface targets and benefits derived from the use of frequency diversity. That is, targets of interest do not behave generally as point targets but rather more like a varying combination of several point targets that all reside within the scattering volume of the radar.

Multistatic Radar Principles

The multistatic radar concept implies the use of a single transmitter and more than one radar receiver to detect a target. Each receiver observes scattered radar energy at different sites and with different geometrical viewing relationships to the incident transmitted wave and scattering volume. The concept differs from that of either the monostatic radar, which has its transmitter and receiver co-located, or the bistatic radar, which has its transmitter and receiver located at different sites. The monostatic radar utilizes one transmitter and one receiver, both of which are co-located and most often use the same antenna. The bistatic radar usually employs different antennas for transmission and reception. The bistatic radar dominated the early days of radar development and was eventually replaced by the monostatic design due to improvements of electronics and inherent advantages associated with single-site radar operations. Extension of the monostatic and bistatic techniques to the multistatic configuration has recently gained renewed interest for a number of reasons. Firstly, the concept provides a simple means of extending and adding to the capabilities of monostatic radars [3]; this can be done through the use of existing radar transmitters [4] or through the use of transmitters of opportunity as demonstrated by [5]. Since the ASDE-3 and many other surveillance radars regularly employ the same sense of circular polarization for both transmission and reception in order to reduce clutter effects of rainfall, bistatic dual polarization offers additional opportunities for signal processing and improved interpretation. The decomposition of the transmitted circularly polarized waves into linearly polarized components leads to the possibility of simultaneous reception of horizontally and vertically polarized waves (or right- and left-handed circular polarizations). The polarization sensitivity of targets is readily illustrated by the bistatic radar cross-sections of conducting spheres and cylinders. These cross-sections indicate that there is considerable sensitivity to the incident wave electric field, particularly at horizontal and vertical polarizations [6]. Such discrimination can lead to intelligent algorithms that filter clutter and improve target detection.

Other reasons for considering multistatic radar principles for airport surveillance radars derive from the dramatic improvements in technology that have occurred during the last three decades. Essentially, advances in communications, computing, signal processing and time referencing have made it possible to economically achieve the advantages that multistatic radar offers.

System Illustration

Fig. 2 demonstrates the basic principles of the multistatic radar applied to an ASDE radar system. The configuration consists of three multistatic receivers that detect scattered radiation from scatterers located on the airport surface. The primary radiation source is the ASDE radar, located on the top of the Control Tower. M_1, M_2 and M_3 signify the location of three multistatic receivers. M_1 is the ASDE monostatic receiver that is co-located with the transmitter. Receivers M_2 and M_3 utilize stationary antennas that cover an extended region of interest in common with the primary radar. These receivers monitor radiation bistatically scattered by targets along the ASDE radar's main beam. Synchronization of timing between the primary ASDE radar and the multistatic receivers allows for the detection and determination of the location of targets throughout the area jointly covered by both the primary radar and the antenna beams of the multistatic receiver sites. The presence or absence of the coincident detection of targets in space by two or more receivers in the set can then be used to confirm the presence of targets seen by the primary radar.

Fig. 2 provides insights into how real and false targets might be detected and placed on a runway. It also aids in examining how different receivers in a multistatic radar would function relative to a known multipath target that produces a false target with the primary radar.

Let T1 represent an aircraft located on runway 4L/22R. This target and its actual location will be detected by the primary radar. In addition, assume that the target also scatters significant energy along the paths from T1 to M_2 and M_3. Provided there is synchronization timing available to these receivers, their returned signals will detect and locate the target T1 in its correct position, coincident with the detection by the primary monostatic radar.

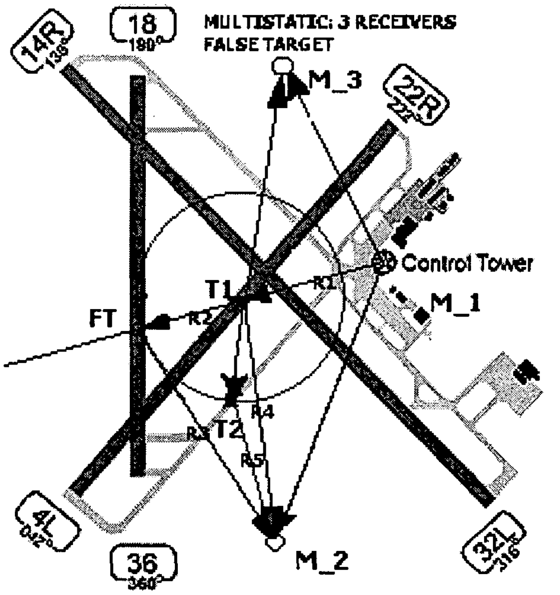

Fig. 2. Illustration of a 3-Receiver Multistatic Radar Configuration at an Airport with the ASDE Radar Located on the Top of the Control Tower.

Consider further the effects of T2, another aircraft on the taxiway parallel to 4L/22R. This aircraft receives bistatically scattered energy from T1 and then backscatters a portion back to T1 which further scatters a portion of this energy back to radar receiver M_1. The radar interprets this delayed energy as an aircraft or other vehicle false target originating at FT at a range of R1+R2 on runway18/36. Typically, the other two receivers, M_2 and M_3, will also receive bistatically scattered energy from T1 as well as multipath scattered energy from both T1 and T2. The direct scatter from T1 to M_1 and M_2 was dealt with in the previous paragraph. Several other multipath propagation scenarios are also possible; two of these are examined in the following paragraphs.

Consider the interpretation of a signal at M_2 that exceeds the threshold of detection and is due to radiation from T2 that was scattered back to T1 and then scattered to M_2. In this situation, M_2 will interpret this radiation as having emanated from a point along the primary beam at a distance greater than R1+R2 from the primary radar.Consideration of M_3 produces the same result, and, except when M_2 and M_3 are symmetrically located relative to the primary beam, the respective false targets are neither coincident with themselves nor the primary radar false target. Thus, careful choice of all the receiver sites can ensure that no coincidence of false targets will result with any two receivers in a multistatic configuration.

A second possiblity is also of interest here. This is the case where the secondary target bistatically scatters energy from T1 directly to either of the receivers. Because of proximity to T2, this would most likely occur for M_2 with the configuration shown in the Fig. 2. This condition would place the false target detected by M_2 at a location between T1 and FT in the figure. Further, bistatic scatter from T2 to M_3 would produce a non-coincident false target at a location beyond FT.

These relatively simple illustrations of a three-receiver mulistatiic radar configuration demonstrate that the simultaneous detection of real and false targets (due to multipath effects) at different receiver sites yield coincident detections only for real targets or for false targets only when special geometries are selected or occur. Thus, careful selection of multistatic receiver sites, relative to the location of the primary radar and surveillance areas of interest on the airport surface, should enable the intelligent fusing of information from the receivers so as to distinguish real targets from false ones that result from multipath effects.

Number of Receivers

The system illustrated in the previous section consisted of three receivers. A more general configuration would consist of any number of receivers, located throughout the airport domain providing coverage of select areas where multipath problems present serious threats to the operational integrity of the ASDE radar. This section considers the number of receivers relative to the expected benefits to be gained from a multistatic radar design. The most relevant performance indices for this evaluation are the probability of detection P_D and the probability of a false alarm P_{FA}. P_D defines the detection performance of the radar for actual targets, while P_{FA} is a measure of the system's vulnerability to declaring the presence of a target when a target does not exist. Both of these parameters are affected by the number of receivers configured within the design of a multistatic radar. A useful way of doing this is to examine P_D and P_{FA} relative to their values applicable to a monostatic radar. The results imply that considerable reductions in P_{FA} are possible while simultaneously achieving comparable or higher values of P_D.

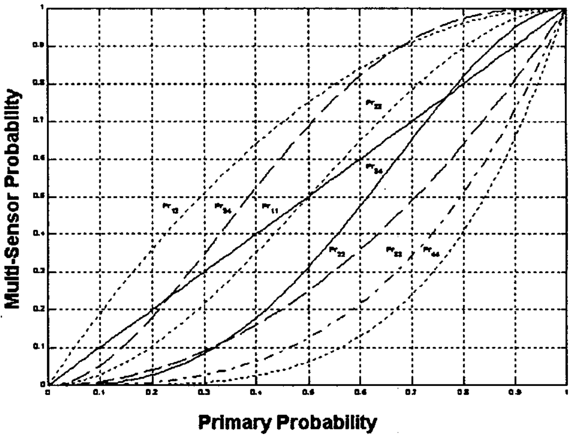

Fig. 3. Detection and False Alarm Probabilities for Various Receiver Combinations; Each Receiver Has the Same P_D and P_{FA} as the Primary Radar.

The analytical process involves a logic that utilizes at least k out of n detections for confirmation of a real target, where m is the number of receivers used to detect a target at a given location and n is the total number of receivers available for the detection in a multistatic radar configuration. The theory uses combinatorics to obtain the probability (Pr) that k out of n events occur [7]. For this application, Pr {at least *k* of the events occur} is the computation of interest. Fig. 3 illustrates results for different combinations of up to four different receivers, assuming that the basic probabilities for each receiver are equal to the primary system probability. The latter implies an expectation that all the receivers behave nearly the same for P_D and for P_{FA}. In this figure, the probabilities may be interpreted as either P_D or P_{FA}. Values of P_D tend to be high, around 0.9, while P_{FA}

tends to be very small, typically 0.1 or even much smaller.

The curve labeled P_{11} represents the performance of a primary stand-alone ASDE radar system; it simply maps the primary probability to itself. P_{11} provides a convenient gage to assess whether the applicable logic results in an improvement or loss of performance. The remaining curves provide insight into what might result from application of a logic based on fusing information from different numbers and combinations of receivers. For example, if there were two sensors (primary radar and one bistatic receiver), P_{12} is the probability that at least one out of two sensors indicates a detection, be it a target detection or a false alarm detection. Similarly, P_{22} is the probability that both sensors produce detections. Examination of the curves in both regions of applicability (high for P_D and low for P_{FA}) shows that a logic utilizing at least one out of two for detection (P_{12}) would increase P_D for all primary detection probabilities; unfortunately, it would simultaneously increase P_{FA}. If one were to employ P_{22} instead, P_{FA} would decrease as required, but P_D would decrease, which is undesirable. Since the objective is to decrease P_{FA}, a logic based on dual detection would have to be used for a two-receiver multistatic radar configuration. Unfortunately, this would have to be at the price of a decreased P_D.

Further examination of the curves in Fig. 3 leads to an interesting result that appears most desirable from a practical design viewpoint. Note that P_{23} or the Pr {at least two out of three detections occur} produces higher probabilities at high values of primary P_D and lower values at low values of P_{FA}. Thus, this configuration (under the assumption of equal probabilities) produces the desirable effect of reducing P_{FA} while simultaneously increasing P_D. Furthermore, the improvements can be quite large, depending on the initial probabilities. For example, employing a logic that requires two out of three for detection of a target would cause P_{FA} to decrease by around 70% for a primary $P_{FA} = 0.1$. The corresponding increase in P_D would be around 8%, if the primary radar detection probability were equal to 0.9. Thus, assuming a nearly equal probability of performance for all the receivers in a multistatic radar configuration, it appears that a three-receiver system would produce significant improvements over the monostatic system.

Since it is not desirable, for practical reasons, to employ a very large number of multistatic receivers in a multistatic radar configuration, the options are limited to a maximum of four receivers for coverage of any designated airport region. The remaining curves in Fig. 3 illustrate performance under these conditions. It is apparent that a practical number of receivers is three with a logic that uses at least two out of three for detection of a target. Consistent with the discussion in the previous paragraph, P_{23} shows that at the larger probabilities ($P_D > 0.5$) this logic would result in an increase in the P_D while at the low probabilities ($P_{FA} < 0.5$) the same logic would result in lower values of P_{FA}. Since the ASDE radar specifications typically operate at P_D □ 0.9 (for real targets of interest) and $P_{FA} \sim 10^{-2} - 10^{-3}$ (for multipath targets), this logic should produce a very large reduction in P_{FA} while simultaneously improving P_D slightly. If a greater reduction in P_{FA} is required, this can be accomplished with a logic that uses at least three out of four; in this case, the improvement in P_D would be restricted to situations where the primary P_D is greater than around 0.77.

Radar Cross-Sections

A critical prerequisite for establishing whether the multistatic radar concept is sound depends on the behavior of the bistatic radar cross sections of airport surface targets. Ideally, the radar bistatic cross sections of airport surface targets of interest should be greater or equal to the monostatic cross sections of these same targets, but this is an unrealistic, if not impossible, expectation. The next best circumstance would be if the bistatic cross-sections of such targets were comparable in magnitude and similar in behavior to the monostatic cross sections.

Stochastic Behavior

In the case of ASDE radar operations, the radar wavelength is very small relative to the size of the targets of interest. Furthermore, the targets are complex objects that have numerous scattering centers, which contribute to the overall scattering cross section observed by the radar within its resolution cell. This implies that the radar cross sections of the targets are generally classified as fluctuating and are typically characterized by a Rayleigh or exponential probability density function. The actual characterization of the target is more complex than this, but the ASDE-3 is configured with frequency diversity capability that enhances and helps to reinforce this representation. This stochastic representation can also arise to some degree through changing the aspect of the target relative to the radar beam or by utilizing schemes that are based on spatial diversity of the target cross section (assumes the target is the same stochastically when viewed at different range or azimuth bins that contain the target). Although far from complete, this description constitutes a practical representation of targets and is generally relied on to analyze and design radar systems for detecting targets resident on the surface of airports. The representation of this scattering behavior, except possibly for values of the radar cross-sections, is applicable to both monostatic and bistatic scatter.

Monostatic-Bistatic Relationships

The radar equation for monostatic and bistatic receivers differs in two important respects – radar cross-sections and range dependency. This section deals with the differences between the monostatic and bistatic radar cross-sections. The effects of range are treated in the section on Bistatic Gain.

Monostatic radar response depends on the monostatic or backscatter radar cross-section σ while the bistatic response depends on the bistatic radar cross-section σ_b. At the radar wavelengths (K_u-band) used by the ASDE-3 radar, the airport surface targets of interest consist of complex radar scattering bodies that yield composite or effective radar cross sections (σ and σ_b) made up of a combination (oftentimes many) of scattering components. Phenomena possibly responsible for these scattering components include: specular reflection, edge diffraction, wedge diffraction, tip diffraction, creeping waves and traveling waves [6]. The problem is further complicated by the facts that the contributing elements sum together as phasors that depend on their electrical location from the radar within the scattering volume and that the electrical size of various elements may be comparable to the radar wavelength, leading to the possibility of resonant behavior. The orientation of the scattering elements relative to the propagation directions of the incident and scattered waves as well as the polarization of the incident and scattered radar waves can also play important roles in the cross-section response. Aircraft and other surface vehicles that dominate airport surface targets of interest conceivably offer opportunities for practically everyone of these scattering components and effects to contribute to the radar cross section seen by a radar that is interrogating the airport spatial domain. Clearly, the complete analytical description and solution of such targets is highly difficult at best, and, as a result, they are considered complex. The practical approach for analysis and design of radar systems used in such applications recognizes this complexity and generalizes on it through a stochastic description of radar target cross-sections [8, 9, 10, 11].

For the monostatic case, the radar cross section of a complex body is considered a stochastic variable that follows a Rayleigh or exponential probability density function distribution. This assumption follows from investigations of the statistics of dynamic cross sections of aircraft in relative random motion. Although this model may not always be applicable in the case of surface radar surveillance (due to the fact that the target may remain static or not move very much within times required for detection), this statistical formulation is usually factored into the radar design, since it offers a means of operation that embodies such concepts as probability of detection and false alarm rate. As noted previously, this embodiment is also advanced through the use of frequency diversity within the ASDE-3 [1, 2].

Consideration of bistatic scatter led to the concept of the bistatic equivalence theorem [12, 13]. This theorem provides a method of estimating the bistatic cross-sections from known monostatic cross-sections. It reads as follows:

> "For perfectly conducting bodies which are sufficiently smooth, in the limit of vanishing wavelength, the bistatic cross section is equal to the monostatic cross section at the bisector of the bistatic angle between the direction to the transmitter and receiver."

The theorem is illustrated in Fig. 5. The phenomenon was originally demonstrated through use of the physical optics approximation when the scattering angle is considerably less than 180°.

Thus, its applicability is somewhat limited, but nevertheless quite important for the ASDE-MP. The critical implication of this theorem is that bistatic cross sections can be expected to vary similarly over a range of values that is comparable to the range of values presented to the radar in the monostatic configuration. Numerous measurements of bistatic cross sections of complex targets since this work support this general conclusion. This important result has also been previously been noted in [12, 13]. This means that the physical behavior of surface targets of interest in a bistatic mode, and thus in a multiple-bistatic or multistatic mode, is expected to be very similar to that of the monostatic or primary radar. This in turn implies that concepts applicable to ASDE-3 radar received signals should in general be applicable to received signals at multistatic sites. Thus, based on the behavior of radar cross-sections alone, transitioning the ASDE-3 from a monostatic to a multistatic radar is fundamentally comparable to having N+1 radars operating simultaneously where N is the number of bistatic sites employed in the multistatic configuration. Since each nearly equivalent-in-performance, yet independent radar in the multistatic configuration would experience different responses to multipath, the overall ASDE-MP system should be able to dramatically reduce the false alarm detection probability P_{FA} associated with false targets while simultaneously maintaining or even improving its reliability in target detection performance as measured by P_D. Accordingly, the arguments put forth in the previous section on Number of Receivers should apply.

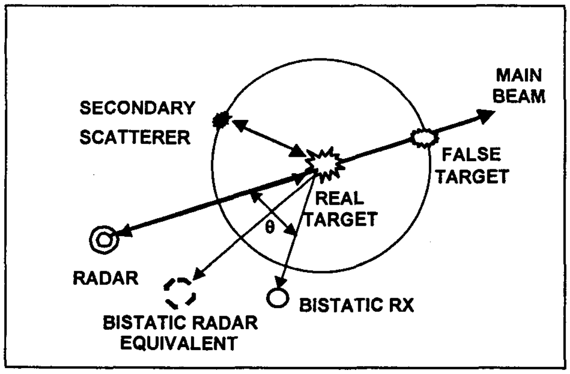

Fig. 5. Demonstration of the Bistatic Equivalence Theorem.

Antennas

ASDE-3 Characteristics

The ASDE-3 antenna characteristics govern a number of important system operational features of the radar [14]. The antenna is quite unique in its design and performance. For example, the radar operates within both the far field and the Fresnel zones of the antenna. The latter extends out to around 4,800 feet due to the large horizontal aperture of around 280 wavelengths. In the far field, the antenna provides a symmetrical azimuthal beamwidth of approximately 0.25° that increases as range decreases back into the Fresnel region (equal to around 0.31° at 500 ft, the nominal minimum operating distance of the radar). The horizontal beamwidth also increases as the depression angle increases downward from the horizontal direction, ranging in the far field from its main beam nominal value of 0.25° to around 1° at a 30° depression angle. The vertical beam pattern is more complex. It is focused in the horizontal direction with a beamwidth of around 1.6°; the antenna response is further shaped to accommodate targets at depression angles down to around 30°.

The typical ASDE-3 antenna's aperture gain variation with range from the radar relative to a target on the surface is illustrated in Fig.6. For distant targets the gain is around 41 to 42 dBi. This value reduces steeply with depression angle until at an angle of around 3° (~ 8,000 ft) its gain is 37 dBi; it further reduces gradually thereafter to around 27 dBi at a 30° depression angle (~ 450 ft). The Fresnel zone field pattern at a distance of 500 ft exhibits a slightly degraded performance in that the vertical beamwidth increases to around 2.5° at 30° depression. Since the crossbeam effects of range counter this degradation of beamwidth, there is no degradation of resolving power of the radar. If one uses the Fresnel zone distance of 4,500 ft. as a reference, the 30 dB cross-beam or azimuthal resolution cell resolution distance would be 22.3 ft. [BW (radians) x range] while at 500 ft. this distance is 2.7 ft. [0.31π x 500]. Thus, even though the angular beamwidth increases as range decreases, the actual cross-beam resolution size of the radar scattering volume decreases considerably (greater resolution) with decreasing range. Thus, the increase in horizontal beamwidth with decreasing range is more than adequately offset by the decrease in range spreading with decreasing range.

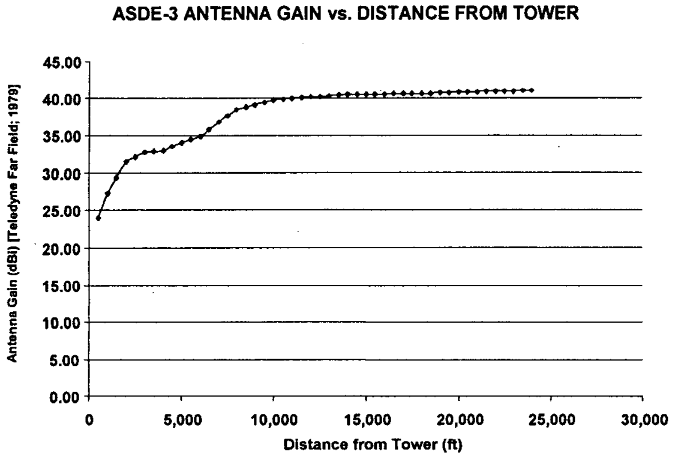

Fig. 6. Typical Aperture Gain of the ASDE-3 Antenna Relative to an Airport Surface Target as a Function of Distance from the Radar.

Multistatic Antenna Characteristics

The key feature of the antenna pattern that impacts a multistatic radar design is the effective gain of the primary radar relative to the effective gain of the antenna at a multistatic receiver site. Ideally, multistatic receiver antennas should be stationary, provide coverage over a reasonable area of interest and restrict coverage vertically to optimize sensitivity to targets on the airport surface. A stationary antenna can provide the needed, limited horizontal coverage of an airport area and remove any need for mechanical or electronic scanning. It presumes that the location of bistatically returned echoes is determined through temporal synchronization of the multistatic receivers with the primary transmissions of the primary radar. Since multipath interferences that produce false targets are usually limited to certain susceptible regions of an airport, multistatic coverage would conveniently be limited to these same areas. Thus, individual multistatic receiver sites need only provide coverage for these same areas, thereby reducing the need for full coverage and increasing the directivity available for detection of targets at the multistatic sites. The optimum vertical coverage provided by a multistatic antenna will depend on a number of geometrical factors, including, for example, the coverage desired, locations available for the multistatic receivers, the distances involved and the heights of the antenna and targets above ground. Typical antenna designs would employ vertical beamwidths ranging between 2 – 5°, while horizontal beamwidths would range between 15 – 60°.

The ASDE-3 antenna gain is relatively modest at short and moderate ranges while the maximum gain is available for target detection at longer ranges from the radar. Thus, the expected loss of sensitivity of a fixed multistatic antenna (that is intended to cover near and moderate ranges from the primary radar and has a high resolution vertical beamwidth coupled with a moderately wide horizontal beamwidth) will not be as large as would be assumed based on the maximum gain of the ASDE-3 antenna (42 dBi). For example, a multistatic minimal antenna vertical beamwidth of 2° will yield corresponding gains of around (28, 25, 22) dBi for horizontal beamwidths of (15°, 30°, 60°), respectively. These gains are to be compared with ASDE-3 effective antenna gains that range between around 27 to 37 dBi in the most interesting radar ranges of interest (out to ~ 8,000 ft range where most multipath false targets occur and cause problems). This example indicates that, depending on range from the primary radar, multistatic receiver sites can be expected to operate with gains that range from being nearly equal to that of the primary radar to values that are as much as around 15 dB less than the primary radar (note that this is a receive only loss). This apparent loss in sensitivity and possible associated impacts on signal to noise ratio will require careful assessment in a final design of a multistatic system. Preliminary evaluation of the ASDE-3 transmitter power levels suggests that there should be ample sensitivity at multistatic receiver sites even with a 15 dB loss in sensitivity relative to the primary radar.

Bistatic Gain

Another factor to be considered is the possibility of compensating part of the probable loss of sensitivity caused by antenna gain differences through gain derived from locating the multistatic (or bistatic) antennas closer to the targets of interest than their distance to the primary radar. The added gain associated with reduced spreading loss of scattered energy would be as much as 6 dB for a multistatic site that is half the distance to the targets of interest than their distance to the primary radar, and 12 dB for targets that are one-fourth this distance. This reduced loss due to locating the multistatic receiver nearer to targets of interest is defined here as bistatic gain (BG). It is simply the dB value of the square of the ratio of the distance from the primary radar to the target to the distance of the multistatic site to the target. An illustration of the BG associated with a multistatic site located at a distance of 1,000 ft from the primary radar is shown in Fig. 7. The direction of the primary radar beam relative to the direction of the bistatic site from the radar ranges from 15° to 90°.

The curves show the additional gain due to the closer proximity of the bistatic site to the target ranges from around 1 dB to 5 dB for distances between 2,000 to 5,000 ft, provided the direction angle does not exceed around 75°. If this angle is small, BG can become quite large, but the closer to 0° the angle is, the closer the multistatic site will be to similarity with the primary radar (except in range to the target). The latter condition would tend to reduce the effectiveness of logically combining radar signals from difference multistatic sites. The 90° curve shows a negative gain over all ranges, since in this case the multistatic site is always farther from the target.

The results of this section show that additional gain, resulting from closer proximity of the multistatic site to the target, can offset some of the loss that would result from disparate gains of the multistatic antenna relative to that of the primary radar.

Note that the variation in BG with location of the primary beam must be accounted for in the processing of bistatic-received signals. Since the precise nature of the differential sensitivity is theoretically known as a function of beam location, this can be readily achieved through appropriate use of sensitivity time control (STC) techniques in the radar digital processing.

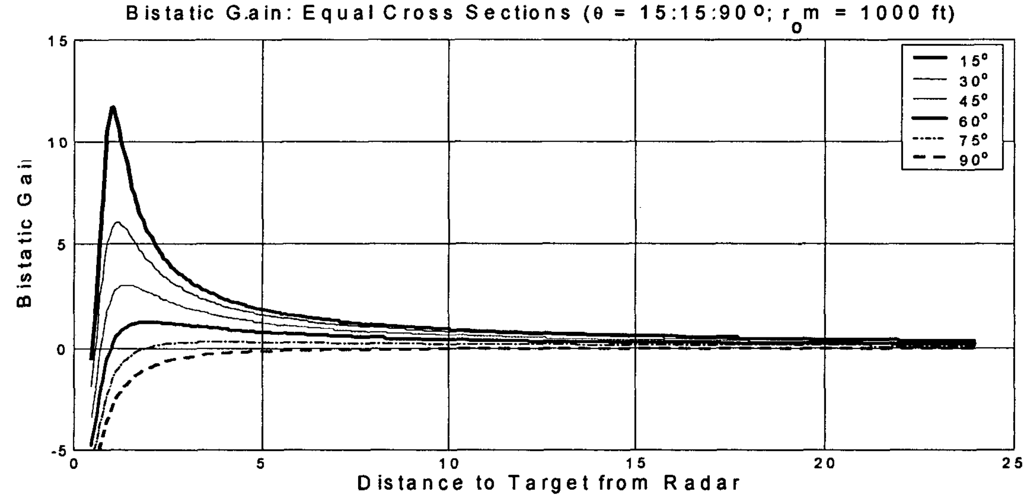

Fig. 7. Illustration of Bistatic Gain (BG) Realized from a Bistatic Receiver Located at a Distance of 1,000 ft from the Primary Radar in Relation to the Distance of the Primary Radar from a Target.

Sidelobes Effects

A possible interference that may affect the multistatic concept relates to the sidelobes response of the ASDE-3 and multistatic antennas. Sidelobes of the primary radar can interfere with the bistatic signals in several ways. First, sidelobe radiation along direct paths from the ASDE-3 radar to multistatic receiver sites can at times produce signals greater than or comparable to returns from radar targets. Fortunately, as far as direct waves are concerned, all real radar targets along the primary radar propagation path will have delays greater than the time necessary for a direct wave from the radar to propagate to the multistatic receiver sites. Thus, direct waves will not pose a problem to the functionality of multistatic receivers, although caution will be required to ensure that their intensity does not cause damage to the multistatic receivers.

Sidelobe contamination will, however, occur when the scattered radiation from targets, irradiated by sidelobe energy, scatters energy to the multistatic receiver and this energy is interpreted as a target along the main beam of the radar. In general, the intensity of this energy is expected to be quite low compared to energy received from targets along the radar's primary beam, except possibly when targets are very near the site of the multistatic receiver. Careful placement of the multistatic sites will reduce this threat to some degree. Another factor at play here is the fact that detection of false targets of this type at the multistatic sites will rarely register at the same location of real targets or at the location of false targets detected by the primary radar or other multistatic sites. It is concluded that sidelobe radiation from the primary radar may require attention in the implementation of a multistatic radar design, even though the expectation is that these effects should not seriously affect performance of a system that relies on coincidence of sensors for the detection of targets.

One feature of sidelobe radiation can be useful in the implementation of the multistatic concept. Direct waves transmitted to multistatic sites via sidelobe radiation can serve as a means for timing synchronization between the primary radar and the multistatic receiver sites; such transmissions can also provide information on the transmitted frequency, thereby helping the receivers to accommodate the frequency diversity of the primary radar transmissions.

Range Cell Resolution

Since geometry forces a bistatic receiver to observe scattering from volumes different than those seen by a monostatic receiver, it is important to understand how this difference might affect the resolution registration of a multistatic receiver site relative to the range resolution of the primary radar. Basically, a monostatic pulsed radar's resolution cell size depends on the radar pulse length and its antenna's beamwidth. For surface surveillance radars, the horizontal (range and azimuthal or cross-range) resolution is of primary interest. Thus, the analysis here focuses on these two dimensions, range and cross-range. Note that the term volume is still occasionally used in the discussion even though its representation is two-dimensional.

The range cell resolution of the monostatic radar configuration is given by $c\tau/2$ where c is the speed of light and τ is the pulse length. of the pulse. The azimuthal resolution is defined in terms of the angular width between the 3-dB azimuthal beamwidth points of the antenna; the corresponding cross-range resolution is given by $R \cdot \Theta$ where R is the radar range and Θ is the azimuthal beamwidth in radians. For short pulse lengths (40-ns for the ASDE-3) and most ranges, the 2-D (range and azimuth) resolution cell is very nearly rectangular in shape. This is illustrated in Fig. 8 along the 30° radial beyond the location of the Receiver. The size and shape of these cells (exaggerated for ease of comparison) form the basis for comparing the scattering volumes that are associated with a bistatic arrangement. An analysis of the bistatic situation (volume of space that contributes to a singular sample of the scattered radar energy observed by a bistatic/multistatic receiver due to a wave transmitted from the radar along a given path) was performed to assess how the surface-based 2-D scattering volumes differ under various placements of a bistatic receiver relative to that of the primary monostatic receiver. The results of the analysis are shown in Fig. 7. These indicate a distortion of the cell shape and an extension of the cell length that depends on aspect relative to the Transmitter and Receiver sites. There is a small difference in the scattering volumes throughout most of the scattering domain. The greatest effects occur when the primary radar energy is directed within around ± 45° from the line connecting the primary radar site to the bistatic receiver location and the range is less than the range to the bistatic receiver site. Under these conditions, the range resolution can be considerably longer than the corresponding monostatic resolution, and, in fact, becomes the entire path length from the radar to the bistatic site when the radar beam is directed towards the bistatic receiver. This arises from the fact that the bistatic receiver sees the integrated forward scattering from all targets in the propagation path from the radar to the bistatic site. Also note that there is a difference in the beginning and ending points of the cells; this difference is not great and, therefore, should not have major influence on the interpretation of measurements.

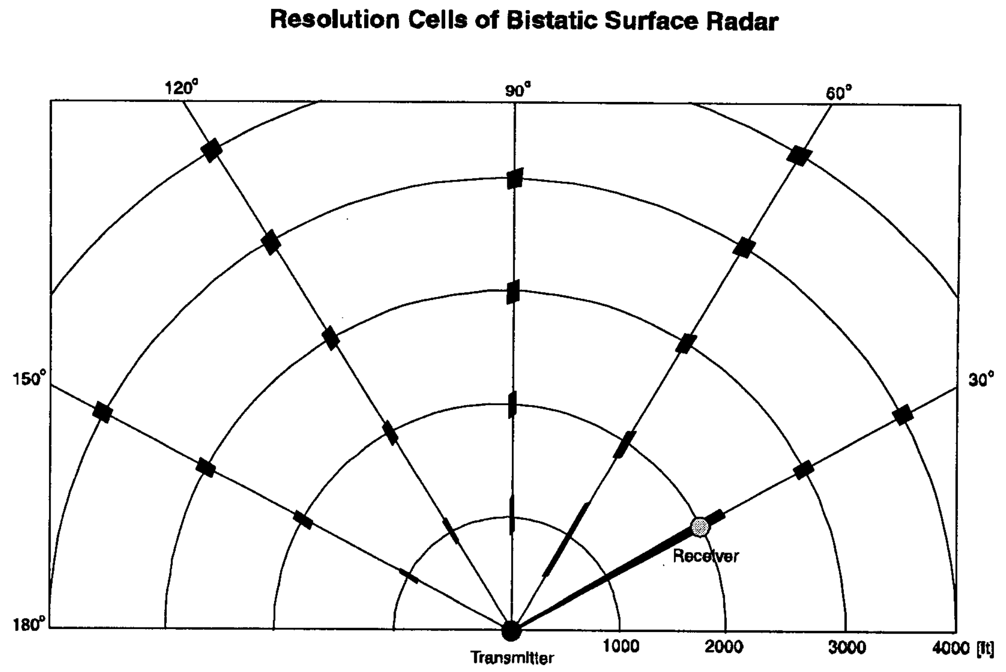

Fig. 7. Illustration of the Shape and Length of a Multistatic Resolution Cell Relative to a Primary Radar. The Multistatic Cell Shape and Size are the Same as Those of the Primary Radar Beyond the Receiver Site Along the Same Radial to the Receiver (30° in the Figure).

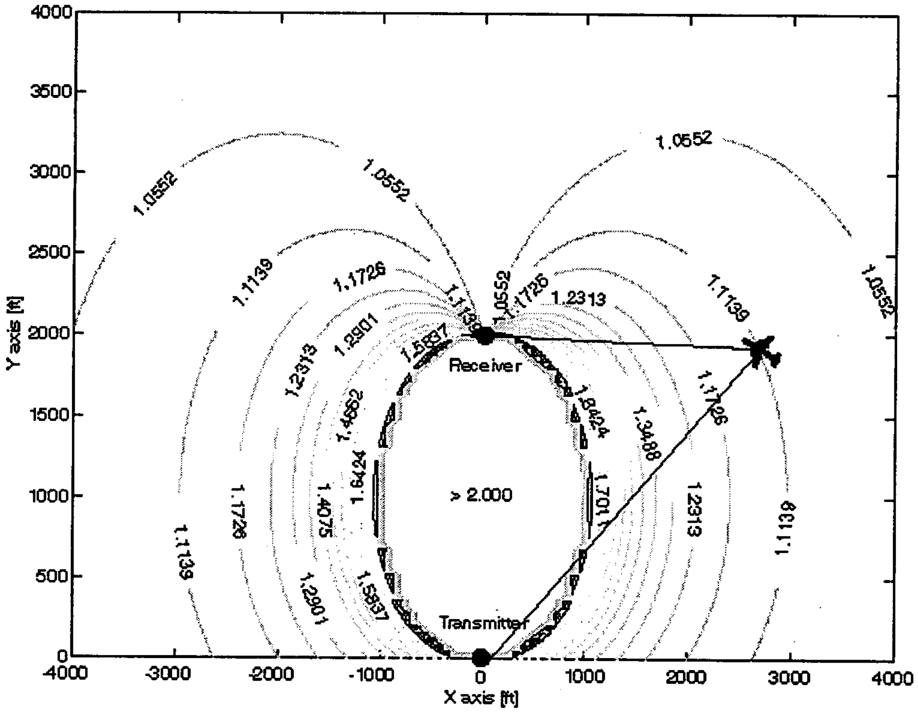

Fig. 8. Illustration of the Range Resolution Distortion ($\delta R_B/\delta R_M$) Associated with Signals Received at a Multistatic Receiver Site Relative to the Locations of the Primary Radar and Multistatic Site.

Another illustration of these same effects is shown in Fig. 8. This presents similar information in terms of contours of the ratio of the range resolutions of the bistatic receiver relative to the range resolution of the monostatic site. A possible application of these results follows. If the largest tolerance to loss of range resolution were a factor of two greater than the inherent resolution of the primary radar, then the inner region bordered by the contour with this value (two) would be excluded for use in detecting targets with a multistatic radar system.

Clearly, this analysis shows that resolution cell size and shape are design considerations for a multistatic radar. Fundamentally, a bistatic site should normally restrict its observations to targets outside the region of unacceptable range resolution, as determined through the analysis demonstrated in Fig. 8. The actual acceptable degradation of range resolution will depend on the application.

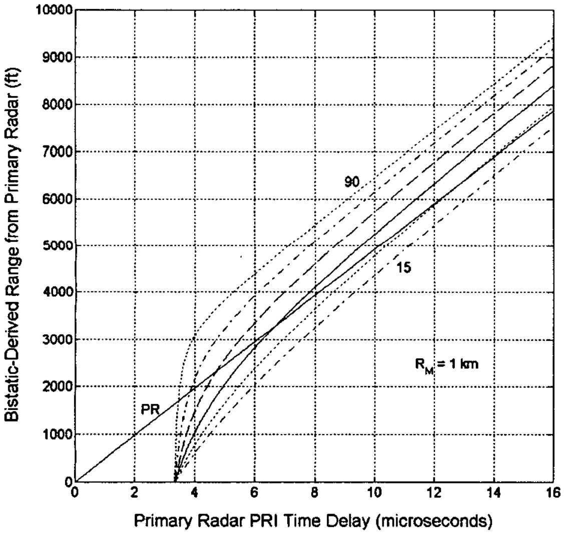

Fig. 9. Relationships Required to Translate Time-Sampled Bistatic Radar Measurements into Primary Radar (PR) Range for Different Angles (15°:15°:90°) Between the Radar Main Beam and the Direction from the PR to the Bistatic Receiver Site when $R_M = 1$ km.

Time Synchronization

Operation of the multistatic radar configuration requires proper interpretation of bistatically scattered radar signals at each multistatic receiver site. This is a relatively simple matter, provided a time reference for transmission of each pulse from the primary radar and the direction of the beam are known at the multistatic sites. These relationships are illustrated in Fig. 9, which shows the dependence of range from the primary radar as a function of the time following excitation of the transmitter pulse. The curves represent different separation angles, ranging from 15° to 90° in steps of 15°, between the direction of the radar beam and the direction from the primary radar to the bistatic site. For these sample curves, the bistatic site is located 1 km (3,281 ft) from the primary radar.

There are a number of ways to obtain synchronization of multistatic receiver sites with the primary radar. These generally involve establishing communications links between the primary radar and multistatic receiver sites. This can be done through hard-wire or fiber optic links or through a radio link. Each PRI transmission must be available, and at least one reference beam direction (preferably North pole transit) per azimuthal rotation of the antenna should be available through these channels. Location finding of the azimuthal reference is also feasible through careful placement of fixed bistatic targets that clearly reveal the beam's location during transit of these targets. Transmission of processed digital video from each multistatic site to a fusion server for interpretation and synchronization is not considered practical because of the high bandwidth requirements of such a system.

Surface and Rainfall Clutter

The effects of surface and rainfall clutter on the detection of targets on airport surfaces of interest are critical factors in the design of the ASDE-3 radar. This radar employs frequency diversity to reduce the effects of surface and rainfall clutter and simultaneously enhance the detection of targets with prescribed Rayleigh radar cross-sections. The same sense of circular polarization is also used for transmission and reception in order to improve the radar's performance in rainfall. Both of these features will have to be accommodated for a multistatic radar enhancement of the ASDE-3 system.

Several ways of accommodating the transmitter's pulse-to-pulse frequency changes in the multistatic receiver appear feasible. One way is to utilize *a priori* knowledge of the frequencies used and their timing sequence; such information can then be employed to switch the frequency of the multistatic receiver's local oscillator to ensure that the receiver produces the same IF frequency for all the transmitted signals. Another way is to employ multiple receiver channels that cover each of the transmitter frequencies; there are a number of ways of combining the signals from these receivers to form a composite received signal. A third way is to use a coded transmitter or other means of sending this information to each multistatic receiver. The implementation of these choices of receiver configuration has been made much easier to implement because of the recent dramatic advances in signal processing technology that have occurred over the last decade.

Polarization Considerations

As previously noted, the ASDE-3 radar employs the classical circular polarization method of reducing clutter due to rainfall. At K_u-band, this technique is susceptible to some loss of utility due to changing polarization caused by primarily two effects: 1. propagation effects that produce differential phase shift and differential attenuation of the horizontally and vertically polarized components of the circularly polarized radar waves; and 2. scattering effects that produce differential amplitude and phase shift between the horizontally and vertically polarized components of the radar waves returned to the radar via scatter from oblate spheroidal raindrops or other non-spherical hydrometeors. Additional alteration of polarization states can take place due to the differential scattering of these same horizontally and vertically polarized wave components when interacting with the airport surface. Thus, the conditional state that is the premise for using circular polarization as a means of reducing the clutter power is limited to short ranges when heavy rainfall is present. Further examination of these phenomena is not included in this paper. Rather, the implications of the polarization state of the incident primary radar wave for a multistatic receiver are considered.

Bistatic radar cross-sections are polarization dependent [6]. Even for simple geometrical bodies such as spheres and cylinders, for example, these cross-sections can vary greatly, especially in the high frequency domain, which is applicable to the ASDE radar. Since the incident radiation can be decomposed into equal amplitudes of horizontal and vertical polarization components, it is convenient to examine the bistatic polarization problem in these linear polarization states rather than dealing with circular polarization. If the scattering centers within the scattering volume are electrically large and made of relatively smooth curved surfaces, the bistatic cross-sections at horizontal and vertical polarizations can be quite similar in magnitude. If the scatterers are made of linear elements such as corners and edges, the polarization responses can be very different with vertical structures expected to produce greater scattering than horizontal structures for vertically polarized waves. The response of these same structures to horizontally polarized waves does not produce a reciprocal result, since the horizontal structures would tend to concentrate its scattered radiation in the vertical plane rather than the horizontal plane, while the vertical structures would tend to produce little if any response. Since aircraft and other vehicles consist of many vertical and horizontal structures, the latter discussion seems relevant. Although very difficult to predict with certainty, the expectation is that the vertically polarized components of the bistatic wave field should typically be greater than the horizontal component. Ideally, both components should be measured with their powers combined as the signal to detect targets. In practice, any two orthogonal polarization states (e.g., right and left circular or linear horizontal and vertical) could be used to extract the maximum power from the bistatic wave field.

Another issue here relates to whether it is possible to achieve some degree of cancellation of clutter due to rain as is obtained with the primary radar through its use of circular polarization. This is not discussed here. However, it appears that improved performance in rainfall may be possible through more intelligent, adaptive processing of the polarization state of the received signal at multistatic receiver sites. A similar approach also offers the possibility of improving the performance of the primary radar [15, 16, 17, 18, 19].

In order to achieve this improvement, dynamic tracking of the power in two orthogonal polarization states of the received radar signals in the absence of any targets of interest would be needed to establish a reference polarization state for the clutter (including any rainfall effects due to propagation). By tracking the coherency matrix for any changes in the degree of polarization present and the orthogonal polarization state to that portion of the coherent polarized signal that makes up the clutter signal, one could conceivably increase the signal-to-noise ratio of the receiver on a resolution cell by resolution cell basis and improve the target detection probability and false alarm rate performance of the radar. Similar concepts have been under intense theoretical investigation by a number of investigators from throughout the world (Giuli and Gherardelli, 1989; Preiser, 1989; Wanielik and Stock, 1989; Holm, 1989; Farina et al., 1989; Poelman and Hilgers, 1989). The technique appears to present a unique opportunity for investigation of these principles for not only the ASDE radars but also for many of the FAA's surveillance radars. Since the ASDE-3 radar employs circular transmission and reception of the same circular polarization state, all that would be needed is to alter the feed of the radar to receive two polarization states and process the data as noted in the following section.

System Architecture

The multistatic radar principles and concepts, outlined previously, provide a basis for outlining a high-level system architecture for the ASDE-MP radar system. Greater detail into an ASDE-MP design requires additional in-depth study and is therefore not provided here. Fig. 10 provides insights into such a system.

The system starts with the ASDE-3 radar from which indicators of both beam direction and each pulse trigger are sent to a communications subsystem. This subsystem transmits the occurrence of each pulse transmission and at least one azimuth direction once each second (the nominal scan rate of the ASDE-3).

The multistatic receiver sites each detect bistatically scattered radiation from the primary radar and also synchronize these signals with the primary radar transmissions for referencing their received signals to the primary radar in both time and azimuth (or beam direction). Each site consists of a radar receiver and processor, a communications receiver for synchronization and a means for sending processed data back to a fusion server for further processing The server function combines detection of targets at each multistatic site, including the ASDE-3, for the determining the presence of real targets and discriminating these from false targets caused by multipath. The fusion server may do additional processing as well, including tracking of targets and conditioning of signals for display or use by other systems such as AMASS.

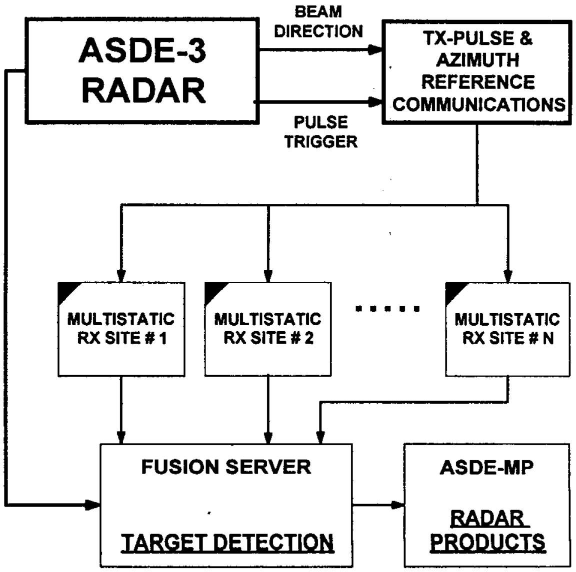

Fig. 10. Possible System Architecture of a ASDE-MP Multistatic Radar System.

Conclusions

Critical elements of a multistatic radar concept for the ASDE airport surveillance class of radars were examined. Essentially, the principles of multistatic radar systems are well understood, and many systems have been successfully applied for various purposes. This study concentrated on issues relevant to the ASDE-MP concept.

The mechanism, typically responsible for the generation of multipath false targets, was reviewed and placed within the context of a multistatic radar concept. It was shown that configurations of receivers and the application of simple logic-based decision making to targets detected by the different receivers could provide a means for increasing the detection probability of real targets while decreasing the probability of detecting false targets.

The bistatic radar cross-section of targets was evaluated relative to the monostatic or backscatter cross-section of these same targets. The bistatic equivalence theorem and other considerations suggest that the bistatic cross-sections should be comparable in magnitude to monostatic values. Thus, all other things being equal, multistatic receiver sites at locations other than the primary radar should provide comparable performance to that of the primary radar.

The ASDE-3 antenna was examined to determine the degree of equivalency in gain that might be achievable within the context of a multistatic receiver site. The results showed that a gain deficit, ranging from around 0 to 15 dB, is anticipated. It was also shown that a portion of this can be recovered through bistatic gain, which accounts for the possibility of the bistatic site being nearer to targets of interest than the primary radar. Antenna sidelobe effects were also examined and found to be a possible source of interference, although each receiver will respond differently to this interference. Thus, the likelihood that this effect would produce coincidence in detection of a false targets detected from this phenomena is considered quite small.

The cell resolution shape and size were found to be reasonably similar to that of the primary radar, except in the vicinity of the region centered around the line connecting the primary radar to the multistatic receiver site. The worst range resolution occurs when the radar beam is directed at the multistatic site and the multistatic receiver sees the integrated effects of targets distributed along that path. The acceptance limits of the degradation in range resolution that applies to any region of the airport surface will depend on the application. Careful selection of multistatic sites will ensure these requirements are accounted for in the system configuration design.

Determining the location of targets detected by multistatic receiver sites depends on knowledge of the time of the primary radar transmissions and the azimuthal direction of the radar beam. It was though that it might be sufficient to know the azimuth direction of one transmission per scan of the antenna. An alternative means of establishing synchronization of the multistatic receiver sites is through use of fixed bistatic targets. In any case, some type of communications link between the primary radar and the multistatic sites is necessary for proper interpretation of signals received at the multistatic sites.

Polarization considerations and effects of clutter due to scattering by objects and surface features other than aircraft and other vehicles were also examine. A preference for use of vertical polarization for bistatic sites was found, but this is inconclusive. Adaptive means of combining orthogonal polarization states to reduce effects of clutter was identified as a possible effective tool for this purpose.

Overall, the results of this investigation provided a reasonable basis for further evaluation of the multistatic radar concept as an enhancement of ASDE radar systems. Accordingly, a proof-of-concept evaluation of the multistatic radar concept, focusing on a number of major findings in this study, was initiated early in 2001 with experiments to be performed in the second half of the year. The experiments will be performed at a major airport where known multipath interferences are known to occur.

References

[1] P. J. Bloom, G. J. Bishop and J. E. Kuhn, 1981, *Detection Performance Evaluation of the ASDE-3 Using Fixed Frequency and Frequency-Agile Operation*, FAA Rept. FAA-RD-81-41, NTIS Doc. ADA099-513.

[2] C. E. Schwab and D. P. Rost, 1985, *Airport Surface Detection Equipment*, Proc. IEEE, **73**, pp. 290-300.

[3] Willis, Nicholas J., 1991, **Bistatic Radar**, Artech House, Boston, MA, 329 pp.

[4] Wurman, Josh, S. Heckman and D. Boccippio, 1993, *A Bistatic Multiple-Doppler Network*, J. Appl. Meteor., **32**, pp.1802-1814.

[5] John D. Sahr and F. D. Lind, 1997, *The Manastash Ridge Radar: A Passive Bistatic Radar for Upper Atmospheric Radio Science*, Radio Science, **32**, pp 2345-58.

[6] G. T. Ruck, D. E. Barrick, W. D. Stuart and C. K. Krichbaum, 1970, **Radar Cross Section Handbook**, Vols. 1 and 2, Plenum Press, New York, 949 pp.

[7] Lennart Råde and B. Westergergren, 1990, **Mathematics Handbook Concepts Theorems Methods Algorithms Formulas Graphs Tables,** Sec. Ed., CRC Press, Boca Raton, FL, 494 pp.

[8] J. V. DiFranco and W. L. Rubin, 1980, **Radar Detection**, Artech House, Inc., Dedham, MA, 654 pp.

[9] N. Levanov, 1988, **Radar Principles**, John Wiley & Sons, New York, 308 pp.

[10] D. P. Meyer and H. A. Mayer, 1973, **Radar Target Detection Handbook of Theory and Practice**, Academic Press, New York, NY., 498 pp.

[11] Rihaczek, A. W., 1969: **Principles of High-Resolution Radar**, McGraw Hill Company, New York, 498 pp.

[12] J. W. Crispin, Jr., R. F. Goodrich and K. M. Siegel, 1959, *A Theoretical Method for the Calculation of the Radar cross Sections of Aircraft and Missiles*, University of Michigan, Rept. No. 2591-1-M, AF 19(604)-1949, AFCRC-TN-59-774.

[13] J. W. Crispin and K. M. Siegel, 1968, **Methods of Radar Cross-Section Analysis,** Academic Press, NY, 426 pp.

[14] F. J. LaRussa, 1981, *ASDE-3 Antenna Development and Test*, U.S. DOT Research and Special Program Administration Transportation System Center Report No. FAA-RD-81-43.

[15] D. Giuli and M. Gherardelli, 1989, *Polarization Signal Processing Techniques*, **in Direct and Inverse Methods in Radar Polarimetry**, ed. by W.-M. Boerner, H. Brand, I. A. Cram, W. A. Holm, D. A Stein, W. Wiesbeck, W. Keydel, D. Giuli, D. T. Gjessing and F. A. Molinet, Kuwer Acad. Pubs., Boston, pp. 909-938.

[16] W. A. Holm, 1989, *Polarimetric Radar Stationary Target/Clutter Discrimination Techniques,* in **Direct and Inverse Methods in Radar Polarimetry**, ed. by W.-M. Boerner et al., Kuwer Acad. Pubs., Boston, pp. 1011-1020.

[17] Farina, A., F. Scannapieco and F. Vinelli, 1989, *Target Detection and Classification with Polarimetric High Range Resolution Radar*, **in Direct and Inverse Methods in Radar Polarimetry**, ed. by W.-M. Boerner et al., Kuwer Acad. Pubs., Boston, pp. 1021-1042.

[18] A. J. Poelman, and K. J. Hilgers, 1989, *The Effectiveness of Multi-Notch Logic-Product Polarization Filters in Radar for Countering Rain Clutter*, **in Direct and Inverse Methods in Radar Polarimetry**, ed. by W.-M. Boerner et al., Kuwer Acad. Pubs., Boston, pp. 1309-1334.

[19] L. B. Preiser, 1989, *On Adaptive Radar Polarimetry: Concepts of Implementation*, **in Direct and Inverse Methods in Radar Polarimetry**, ed. by W.-M. Boerner et al., Kuwer Acad. Pubs., Boston, pp. 989-998.