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Range Commanders Council

ELECTRONIC TRAJECTORY MEASUREMENTS GROUP

THE RADAR ROADMAP

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THE RADAR ROADMAP

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Preface

The Radar Roadmap is a new type of document for the Range Commanders Council (RCC) Electronic Trajectory Measurements Group (ETMG). This document is a statement from the technical community of the instrumentation radar requirements for 10, 20, and even 30 years into the future. Like an automobile roadmap, it is intended to show where we <u>can</u> go and the best routes to get there. It is not a document that shows where we <u>must</u> go. This is the first time a visionary guidance document like this has been attempted by the ETMG. It is our hope that the document will be a living, growing document, with periodic updates.

The Roadmap project is really a joint effort. It is an ETMG document, but it is also intended to satisfy the needs of the Office of the Secretary of Defense (OSD) Central Test and Evaluation Investment Program (CTEIP) manager. A tri-service team, consisting of Christopher Weal (OSD), Donald Sammon (Army, White Sands Missile Range (WSMR)), Richard Stepanian (Air Force (30th Space Wing), and Grant Mills (Naval Air Warfare Center Weapons Division), put together the radar roadmap. In addition, Elwin Nunn (WSMR), Earl Comstock (Newtech), and Dr. Richard Mitchell (Mark Resources, Inc.) provided significant contributions. Finally, OSD provided a substantial amount of the funding for this effort, particularly for the contractor support.

Abstract

Instrumentation radar has played a very significant role in testing and training for more than 50 years. Along with optics, it has been a major supplier of time-space-position-information (TSPI). With the advent of the Global Positioning System (GPS), the need for instrumentation radar for TSPI has been called into question. Is radar still needed? Or can it be replaced by GPS? The members of the ETMG argue that radar is still needed. A study of requirements at over 25 test and training ranges has shown that radar, far from being passè, is needed more than ever. Radar is needed for TSPI on objects that cannot be instrumented for GPS. It is also needed for a variety of specialized measurements, including radar cross section (i.e., stealthiness), characterization of debris, and assessment of damage at intercept.   This paper discusses the future needs of instrumentation radar and presents the radar roadmap (i.e., the plan) for satisfying those needs at the test, training, and operational ranges for 10, 20, and even 30 years into the future.

1.0 Introduction

Radar Roadmap is a plan for taking the radar capabilities of the Department of Defense (DOD) test and training ranges into the 21st Century. It was developed by the Electronic Trajectory Measurements Group of the RCC and is designed to make the DOD radar community more capable, more flexible, more versatile, more efficient and more cost effective. And just as important, it will provide for new or enhanced capabilities needed for future testing. Like an automobile roadmap, it is intended to show where we <u>can</u> go, and the best routes to get there. It is not a document that shows where we <u>must</u> go.

Why radar? Isn't radar passè? Won't GPS do everything radar now does? Hardly! There are still plenty of tasks where radar is needed. Radar is needed for TSPI and other measurements on non-cooperative targets. These include (1) objects too small to be augmented for GPS coverage, (2) objects that cannot be augmented cost-effectively, (3) objects that cannot be augmented because it would alter the test conditions, (4) objects that are under production and cannot be augmented, (5) objects for which the radar cross section (i.e., stealthiness) is being measured, (6) objects created by the impact of other objects, and (7) objects for which the extent of damage must be estimated after impact. Radar will also be needed for objects which are tested for (or in the presence of) GPS jamming and objects which must be independently monitored for flight safety purposes, whether these objects are cooperative (i.e., have a radar transponder) or not.

Why improve, upgrade or augment radars at DOD test and training ranges? Don't we have enough radars already? The answer is that we don't have the necessary mix or all the needed capabilities. We need more multiple-object trackers and fewer single object trackers. We don't have wideband imaging radars for measuring miss distance and attitude to the accuracy required. We lack the capability of programming the radars to operate semi-autonomously under conditions which are stressing to the operator. We lack the capability to remotely control radars from long distances. We are short on inexpensive CW radars which provide enormous detail on events from unambiguous Doppler data. Finally, we need to develop an active phased array for multiple-object tracking radars for future tests involving many-on-many and tests at long ranges requiring both high Pulse Repetition Frequencies (PRF) and long pulse widths.

The 21st Century radar fleet will have all the advanced capabilities of modern radars. Imaging radars will replace/augment ordinary instrumentation radars. Multiple-object trackers will be added where needed. And small inexpensive continuous wave (CW) radars will provide information on tests in near-launch and other hazardous areas. The 21st Century radar fleet will indeed be better, smarter and more effective. In addition, it will be more efficient to build, to operate and to maintain.

2.0 The Ultimate Instrumentation Radar

The ETMG has conceptually designed the Ultimate Instrumentation Radar (UIR). In truth there will not be just one UIR but a family of them: multiple object trackers, single object trackers and CW radars. Each UIR will incorporate various elements of a family of advanced technologies suited to the unique mission of the particular test/training range using it.

To illustrate this family of technologies, let's discuss the Multiple-Object UIR (MO-UIR). It will be a sophisticated radar which incorporates most of the advanced technologies (i.e., all except polarization diversity). The MO-UIR will be a self-contained, mobile, fully coherent, multiple-object tracking instrumentation radar system. It will have range resolution of one foot or less for imaging of tracked objects. It will have an active phased array for the high duty cycle/high average power needed for long range tracking. It will be fully programmable through the use of a radar control language, and thus be able to collect data on complex and rapidly changing scenarios. It will be extremely stable through the use of digitally generated linear FM waveforms. It will be extremely versatile, using digital beam forming to form multiple receive beams simultaneously, and permitting operation at the system PRF on all targets. It will be remotely controllable for use in hazardous/difficult-to-access areas. It will utilize extremely accurate and precise timing for combining data from multiple sources. It will record all raw data so the test can be processed in different ways for different information. It will make maximum use of commercial off the shelf hardware, solid state components, digital control, built-in test equipment and automated calibration for maximum reliability, maximum maintainability and minimum life cycle costs. And finally, it will be imbedded in a real-time control and display system which will provide the user with finished data products either during the test or shortly thereafter, depending on the desired data product. We now consider each of the major characteristics of this radar in more detail. A parenthetical note showing its relevance to single-object trackers (SOT) and CW radars will follow each technology.

2.1 <u>Full Coherence.</u> Many of today's instrumentation radars are coherent, meaning the phase relationship between the transmit and received pulses is maintained or measured. Coherence allows measurement of phase change due to motion relative to the radar, whether the motion is translational or rotational. Coherence also implies Doppler measurement capability since Doppler is the negative time derivative of phase. Assuming adequate motion compensation, Doppler can be highly resolved, and highly resolved Doppler is an essential component of radar imaging. Coherent radars can be fully coherent or coherent-on-receive. Fully coherent radars are, as the label suggests, coherent under all conditions. By contrast, the typical coherent-on-receive radar is coherent only in the first range ambiguity, or when the target is close enough for the first pulse to return before the next is transmitted. Many of today's instrumentation radars are fully coherent (e.g., AN/MPS-36 and AN/MPS-39 a.k.a. MOTR). Therefore, little development will be required to make the MO-UIR fully coherent. (Applicable to SOT; inherent to CW.)

2.2 <u>High-Range Resolution.</u> High-range resolution is achieved through wide bandwidth. Typically, the frequency of each transmit pulse is linearly swept over the entire bandwidth. The

greater the swept bandwidth, the smaller the resolution of the range measurement. A bandwidth of 500 MHz yields a range resolution of about one foot. High range resolution is, along with Doppler resolution, an essential component of radar imaging. Most of today's instrumentation radars do not have high range resolution, but the techniques are well-known, the technology is mature, and relatively little development will be needed to incorporate it into the MO-UIR. The requirements are that (1) the signal be digitally generated, highly stable and low noise, and (2) frequency steering of the phased array by the frequency chirp be kept within acceptable bounds. (Applicable to SOT but not CW.)

2.3   Digital Waveform Generation.   Digital waveform generation is the process for obtaining the linear FM sweep needed for high range resolution. The technology already exists for digitally generating the linear FM sweep, so little development is needed in this area. (Applicable to SOT but not CW.)

2.4   Active Phased Array.   A phased array will be necessary for the radar to track multiple objects with any appreciable angular extent. The typical single-object tracker dish antenna has a field of view of 1° or less, whereas multiple-object instrumentation radars can have a 60° field of view. MOTR has a phased array so no phased array development is needed per se. However, the MO-UIR needs an active phased array. Rather than providing a high power RF field to an array which introduces a phase shift at each element in order to form the beams, the active array will contain a low-power amplifier at each element and low power illumination of the array (or no illumination if each element contains a transmitter). These elements will be solid state components and will be capable of near-CW operation. This means that very high duty ratios (up to 50%) will be possible, thus greatly boosting the average power, hence the loop gain, and hence the tracking range of the radar. A radar like MOTR could, when equipped with an active phased array, track small orbiting satellites. An active array will also exhibit the graceful degradation promised for phased arrays, but often rendered irrelevant by the single-point failure of the high-power transmitter. A considerable amount of time and effort will be needed to develop an affordable active array for the MO-UIR. (Not applicable to either SOT or CW.)

2.5   Digital Beam Forming.   A phased array allows the use of digital beam forming, a process of digitizing and recording the output of each array element so that, in subsequent computer processing, multiple beams and strategically placed nulls can be created. By creating multiple beams on receive, multiple objects can be tracked simultaneously at the system PRF instead of sub-multiples of the system PRF, and beams can be formed to locate items of interest that were illuminated but not tracked. On the transmit side, the beam can be shaped to illuminate just those objects of interest. Digital beam forming, if included, must be an integral part of the active array development and stretch processing will have to be included to keep the number of recorded samples manageable. (Not applicable to either SOT or CW.)

2.6   Radar Control Language. The MO-UIR will need to be able to track multiple objects in a complex, rapidly changing environment -- a situation that will often overtax the human operator. To remedy this situation, a radar control language (RCL) will be developed. RCL will be a high level language that is programmed prior to the mission to control the radar in real-time. It will be possible to program for deployments, dispenses, intercepts and other events, changing the radar's behavior as the test scenario unfolds. Development of the RCL should be straightforward but it must be done carefully, since RCL will have to make operator-type decisions in real-time. An expert system may have to be developed to help program the RCL. (Applicable to SOT but probably not needed for CW.)

2.7   Automated Setup and Calibration. The MO-UIR will be automated for set-up and calibration. Setup includes tuning the radar, verifying the loop gain, testing the performance of transmitter and receiver, phasing receiver channels, scaling error gradients, and increasingly, setting parameters and verifying the correct operation of software-based subsystems. Calibration includes measurement and validation of the systematic errors that affect a radar track, calibrating the range and angle measurements, and setting in delay values for transponders. Calibration is what sets instrumentation radars apart from surveillance radars and other tracking radars. Instrumentation radars must be set up and calibrated frequently to ensure the necessary accuracy and precision. Automating these processes will greatly reduce the effort needed and hence the number of highly-skilled personnel. Many instrumentation radars have some degree of automated calibration already. Some additional development will be needed to more fully automate calibrations, but this should be straight-forward engineering. (Applicable to SOT; perhaps applicable to CW.)

2.8   Real-Time Data Recording, Processing and Display.   All data collected and all actions taken by the MO-UIR must be recorded for subsequent processing and analysis. Many of the measurements will be obtained and displayed in real-time (e.g., Range-Time-Intensity or RTI plots). Other measurements such as miss distance, attitude and damage assessment will rely on radar imaging which requires an extensive amount of processing on an expert-system imaging workstation and, in the case of miss distance, requires the combination of data from multiple radars. Most of the radar signal processing development has or will have been done by the time the MO-UIR is developed. White Sands Missile Range (WSMR) has developed a radar imaging workstation under contract with MARK Resources, Inc., Torrance, CA during the past two years. Work has begun on the expert system to assist in the processing of the data. Some other development will be needed on the real-time recording and display, but this should be straight-forward engineering. (Applicable to SOT and CW.)

2.9   Real-Time Control. In real-time, the MO-UIR will be controlled in a variety of ways. First, it will be controlled in general by a human operator. Second, it will be controlled by the radar control language which will be programmed and activated by the human operator. Third, it will be guided by an expert system. Fourth, it will be synchronized with other radars by a central control facility so that the high-duty pulses of one radar do not interfere with another radar. And

fifth, it's overall operation and data products, raw or finished, will be coordinated by the central control facility in charge of the test. Data from all sensors will be collected and fused in real-time at a central site. (Applicable to SOT and CW.)

2.10 <u>Reliability.</u> The MO-UIR will be designed and built to be reliable, -- both the equipment and the calibration of the radar. Present instrumentation radars are maintained and operated by highly skilled on-site technicians who are constantly repairing and/or calibrating to keep the radar in top condition. Future radars will have to be more reliable because (1) they may have to be operated remotely and (2) the number of highly-skilled technicians will be reduced to reduce labor costs. Improved reliability will mean added initial costs but the engineering to achieve the reliability is straightforward. A reliable design should also use modular units, as this eases maintenance and improves the availability of the system. The design should also avoid, as much as possible, components or subsystems that the marketplace does not support. The use of reliable, modular, and Commercial Off-The-Shelf (COTS) components should be a goal of new radar subsystem designs. (Applicable to SOT and CW.)

2.11 <u>Polarization Diversity.</u> The MO-UIR probably will not have polarization diversity. It would be extremely difficult to implement in a phased array. It may be used in some SOTs, however, where measurement of polarization is important to the test (e.g., verifying missile seeker characteristics). (Applicable to SOT.)

3.0 MOTR vis-à-vis the Multiple-Object UIR

The first Multiple Object Tracking Radar (MOTR) was designed in the mid-80s and delivered to WSMR more than a decade ago. If a MOTR were to be built today using the original specifications, it would be out of date. However, MOTR has been almost continuously improved since it became operational. All four DOD MOTRs have been modified to track 40 objects, whereas the original MOTR could only track 10. The system PRF has been increased from 1280 to 2560 samples per second. New data recording systems and new computers have been installed. The capability of recording multiple range gates, for measuring miss distance and characterizing debris after intercept, has been incorporated. And new improved calibration software has been added. All of these improvements should be folded into any MOTR that is purchased in the future.

Ongoing MOTR studies and prototype developments will further increase the MOTR's capabilities. Coherent clutter rejection, aelotropic tracking filters, Doppler tracking, wide bandwidth and semi-automated operator consoles are either under development or have been extensively studied. All of these improvements can be added to any new MOTR with very little additional development.

Thus, the MOTR, rather than being an obsolete radar has been modernized as we've gone along. It is now <u>the</u> state-of-the-art mobile multiple-object instrumentation radar, and is fully

capable of meeting the requirements of many test and training ranges. MOTR now has (or will have) many of the key elements of the MO-UIR, -- features such as multiple-object tracking, full coherence and multiple range gates. It's not yet a MO-UIR, since it does not have an active array, digital beam forming, wide bandwidth, and so on, but if it continues to be systematically improved, it can be expected to evolve into an MO-UIR. In fact, it is our belief that all MOTR improvements should, as much as possible, incorporate features of the MO-UIR, while avoiding features that are incompatible with it.

4.0 The Radar Roadmap (i.e., the plan)

This plan addresses what we see as the relevant radar solutions to the perceived requirements of 10, 20, and 30 years into the future. It includes many excellent cost-effective solutions that are already in existence, and it includes various developments that are needed to meet the more stringent requirements anticipated for the future.

4.1   <u>Multiple-Object Ultimate Instrumentation Radar (MO-UIR).</u> The MO-UIR will take several years to develop and should be pursued as a tri-service effort. The development of the active phased array, with digital beam forming, should be begun immediately because it is the highest risk, longest lead time item. An operational radar should be possible within ten years. MO-UIR developments should be closely coordinated with the MOTR developments, working toward the point where the two converge (i.e., where any MOTR can be upgraded to become an MO-UIR). Designing for ultra reliability should be a very high priority.

4.2   <u>Multiple-Object Trackers.</u> Where requirements now exist for multiple-object trackers, the modernized MOTR should be purchased. It is a very versatile radar, capable of tracking forty objects and collecting data in multiple range gates. It is a fully coherent, 1 MW radar with system PRF of 2560 and pulse widths of ¼, ½, 1, 3 1/8, 12½ and 50 µs. Its major deficiency is the lack of bandwidth (i.e., range resolution). It is also a very costly radar, but the cost varies considerably with the number purchased. The manufacturer has recently quoted the following prices: $30M for one, $50M for two ($25M apiece) and $60M for three ($20M apiece). The three services should go together to purchase at least three MOTRs so the price savings can be realized. Actually, we have already identified the need for 7 to 9 additional MOTRs: WSMR, NM (2), ESMC at Cape Canaveral, FL (1), WSMC at VAFB, CA (1), NAWC at Pt Mugu, CA (1 or 2), PMRF at Barking Sands, HI (1 or 2), and AFWTF at Roosevelt Roads, Puerto Rico (1).

Existing MOTR-class radars will have to be updated, particularly in the console and computer areas. The consoles need to be completely replaced and the computers need additional processing capability. It would also be wise to separate the basic radar functions from the control functions, and put them on separate computers. Therefore, the three services should arrange for an on-going product improvement program for the MOTRs. This program would prevent obsolescence such as has occurred with the consoles and provide improvements such as was done in adding in the 124 range gates. The MOTR product improvement program will also

provide some of the early development for the MO-UIR. In fact, all of the advanced technologies except the active array and digital beam forming could be incorporated through relatively straightforward engineering in the next few years. The MOTR is already fully coherent so no development is needed here.   Automated setup and calibration have been incorporated to a large extent but will be increased. High range resolution, including digital waveform generation, and radar control language have been studied for implementation.   Real-time data recording, processing and display and real-time control will naturally grow as the high range resolution and radar control language are implemented. And improved reliability -- both equipment and calibration -- should be a high priority for all upgrades.

4.3   Single-Object Trackers.   For many test and training applications, low-cost single-object trackers are a viable option. Currently, if an AN/FPS-16 radar antenna and pedestal are provided, a new radar can be procured via the Instrumentation Radar Support Program (IRSP) contract for about $2.2M. These radars have the same tracking performance of an original AN/FPS-16, that is: 0.1 mil angular accuracy and about 20 ft range, with noise around 3 - 4 feet. Of course, they provide only range, azimuth and elevation data, since they are neither coherent nor wideband. A program could be initiated with the IRSP contractor to convert these to a modular design. The same electronics could be used with different pedestals, the radar could be converted to use a 1 MW klystron or a cross field amplifier to provide stable output for use with moving target indicator (MTI) or pulse Doppler tracking. A larger 5 MW transmitter could be used with an existing 30 ft dish for high power applications. As much as possible, high-power solid state transmitters should be used, as has been done at the Air Force Eastern and Western Ranges. MTI, remote control, and Doppler tracking could be modular additions. Already the IRSP radar is modularized, although some functions in control, ranging, and data handling could be more effectively combined into a single computer chassis with reduction in wiring and parts. The contractor has built different parts of the radar at different times to sell to various domestic and foreign customers, so some parts are of current design and others are nearly obsolete. Development funds should be provided to produce a modular, standardized, single-object tracking radar with options, including Doppler, high range resolution, and other advanced technologies as needed. Regular updating should be done, high priority should be given to improved reliability, and imaging capability should be added as needed.

4.4   Imaging Radars. The current instrumentation radars (whether a single or multiple object tracker) can be augmented by a small, special purpose, slaved (i.e., non-tracking), wideband data collecting radar. WSMR and MARK Resources have designed such a radar. Other characteristics of this radar include the following: X-band (8.5 - 10.55 GHz), transportable, monostatic, 500 MHz (1 ft resolution), solid state, digitally generated linear FM chirp, digital pulse compression, 15 to 140 km ranges (but easily extendible to 280 km), 1° or 2° beamwidth, 1000 to 2000 s/s PRF, RTI plots displayed in real-time, quick-look image processing and data combination on specialized workstation recently developed. Four of these radars are needed to accurately measure attitude, miss distance, object deployment and extent of damage at ranges up to 140 km. Cost of one system, including five radars (one spare) and associated equipment, is

expected to be $15M or less. This system, being all solid state, should be very reliable. CTEIP funding for these new imaging radars should be provided.

Wide bandwidth can, of course, also be achieved by modifying existing tracking radars; there are several of the test and training ranges where this would be the best approach. One company claims to be able to modify an existing single-object tracker to produce an imaging radar for about $4M each, assuming the radar is fully serviceable before modification. Another company is working on adding wide bandwidth to the multiple object trackers. Each range should buy these upgrades as needed.

4.5   CW Radars. In many tests, the customer needs to know what happened and when it happened, that is, to identify and characterize events. Often these events occur early in the launch of a missile but also occur frequently in the terminal period when munitions of one type or another are dispensed by either missiles or projectiles. These events often can be adequately characterized by their Doppler, provided the Doppler ambiguity interval is sufficiently wide. Although coherent pulsed radars can obtain Doppler on the tracked objects, the ambiguity interval is usually too small to allow the various Doppler's to be sorted out. CW radars, by contrast, have a theoretically infinite ambiguity interval which can be digitized at a rate high enough to preserve the necessary Doppler interval. CW radars are also excellent for providing TSPI on direct fire weapons and mortars. Small transportable, solid state CW radars are inexpensive, typically $1M - $3M. They are also very reliable. Each range should buy CW radars and incorporate advanced technologies as needed.

4.6   Data Fusion. Radar data products are being improved at many of the ranges by merging radar data with data from other instrumentation systems. For example, video trackers, mounted on a radar antenna can be used to track objects visually. A new data fusion concept is merging radar data with data from the Global Positioning System (GPS). For this a GPS receiver is connected to a radar transponder and provides a convenient link from the airborne GPS receiver to the ground. Other examples are use of infrared optics and laser trackers with radars, and the use of radar range measurements to automatically focus optical systems. Each subsystem uses its own strengths to boost the overall quality of the data product. Data fusion should be a high priority at ranges that utilize multiple sensors.

4.7   Pre-mission Planning. Pre-mission planning and simulation are being developed or improved at several ranges. The customers themselves often simulate the test to be performed (e.g., the encounter of a re-entry vehicle and a theater defense missile), so the range planner does not have to do anything in this regard. However, the radar planner needs to simulate the placement and performance of the instruments in conjunction with the simulated test. In effect, the planner must demonstrate to all parties that (1) no radar will be lost to terrain shadowing, ground clutter, low S/N, etc. and (2) the data will be sufficiently accurate for the purposes intended. As test resources shrink, and hence fewer and fewer tests are conducted, it becomes imperative that the few tests conducted be conducted successfully. Therefore, pre-mission planning and simulation

become more valuable every year. Each range should incorporate technologies for pre-mission planning as needed.

4.8 Miscellaneous. First, specialized uses of instrumentation radars should be considered as particular circumstances of the test/training ranges dictate. These include fine-line Doppler tracking, multiple-object tracking in the single beam of a dish antenna (e.g., the tracking of incoming multiple warheads/decoys or dispensed submunitions), and increased angle resolution through the use of multiple mutually-coherent radars. And second, alternative technologies such as impulse radar and multiple-object bistatic radars should continue to be studied. The former allows high resolution without the use of pulse compression techniques and the latter promises cheaper systems by using a single transmitter to illuminate the target for multiple receivers.

5.0 Additional Remarks

The DOD test and training ranges are configured for a variety of different missions, and therefore require a variety of different combinations of radar instrumentation. A few ranges are making extensive use of GPS, particularly where manned aircraft testing is involved, but even among these ranges, some radar coverage is needed. Some ranges have the need for multiple-object trackers, particularly where multiple objects are dispensed or many objects are in the air at the same time. Other ranges are doing just fine with single-object trackers, although several radars may be used. Still other ranges need a mix of multiple-and single-object trackers. Several ranges are now expressing a need for imaging radars to make precise measurements and to detect and characterize events at long ranges or high altitudes, whereas other ranges are doing just fine with TSPI data only, not even using available coherent information. A few ranges expressed a need for a modest increase in loop gain (e.g., for improved shuttle tracking), and the two ranges involved in space lift operations expressed the need for a large increase. And finally, many ranges are combining radar data with optics, GPS, on-board and other types of data to produce a more complete data product.

Whatever the mission or whatever the configuration of radars, most ranges expressed similar concerns. They need periodic updates of equipment to replace antiquated, insupportable, or inadequate components. They need higher reliability and reduced operating costs, including more reliable components, more standardization of components and data products, reduced crew size, more automation, and even remote operation. And they need to be able to leverage off each other's developments. In this age of tight budgets, tri-service development is essential, and coordination and information interchange through the ETMG are more important than ever.

APPENDIX A

ISSUES CONCERNING THE RADAR ROADMAP

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ISSUES CONCERNING THE RADAR ROADMAP

by
R.L. Mitchell of Mark Resources Incorporated

13 February 1998

In this report we comment on several issues related to the Radar Roadmap being developed at White Sands Missile Range. The first 11 sections deal with the design of a new wideband instrumentation radar system that is controlled by (slaved to) existing tracking radars, while the remainder is more general.

1.0 Choice of Frequency Band

One of the outstanding issues for the new wideband instrumentation radars (that are slaved to existing tracking radars) is the choice of frequency band. Anything below C-band is ruled out because of insufficient equipment bandwidth. C-band is not a good choice either because the tracking radars, which are needed to control the wideband radars, are already at C-band. Since the wideband radars would occupy the entire 500 MHz band that is available at C-band, the tracking radars will receive some portion of every wideband pulse, and could be interfered with (on the other hand, the tracking radars should not present a problem to the wideband radars). Although it is possible in theory to schedule the wideband transmissions so the interference falls outside the tracking windows of the tracking radars, it is not very practical to do so.

In order to avoid interfering with the C-band tracking radars, the wideband radars must be at least at X-band. In fact, X-band is ideal for several reasons: (1) the frequency is high enough to provide good Doppler sensitivity, yet low enough so that target backscattering is well behaved; (2) atmospheric attenuation is much less than at higher frequencies; (3) rf components and antennas are readily available; and (4) the bandwidth limit of the transmitter and other components is wide enough to provide two separate 500 MHz bands to help solve the interference problem among multiple wideband radars operating simultaneously. The only potential problem is that some systems under test may have on-board electronic equipment at X-band. Although it is extremely unlikely that the wideband transmissions could ever affect the on-board equipment (because such equipment must be designed to operate in a hostile environment), we could entertain the possibility of operating the wideband radars in other bands. It appears that the frequencies from 10.7 to 13.2 GHz are allocated to commercial users, so to avoid conflict, our choices for a 1 GHz tunable band seem to be from 9.7 to 10.7 GHz, or somewhere above 13.2 GHz. There is a significant price to be paid in terms of power, however, if we operate at or above 13.2 GHz.

For the applications of interest, the antenna must illuminate a certain sector, regardless of the choice of frequency, so the antenna gain is essentially independent of frequency. Of the remaining parameters in the radar range equation, three are frequency dependent: wavelength-squared, atmospheric attenuation, and noise figure, and all favor a lower frequency. Together, the difference in performance between 10 and 13 GHz is about 3 dB based on the signal-to-noise ratio, assuming that everything else remains the same. One can argue that since the higher frequency offers more Doppler sensitivity, the difference should be closer to 2 dB. Either way, the difference would have to be made up by increasing the transmit power, which would be especially costly for the solid state technology.

There is another important consideration. Although solid state transmit modules are available in the band from 9.7 to 10.7 GHz, they may not exist at 13 GHz, which would force us to utilize the tube technology. Tubes operate at a low duty ratio, which means the A/D converter would have to operate at a proportionately higher rate, which is undesirable. Tubes are also likely to be less stable.

It may not even be necessary to operate in a non-conflicting frequency band because the magnitude of the interference problem is not very significant, as we discuss next.

2.0 Assessment of Interference

The bandwidth of the X-band equipment on board a target is likely to be very narrow compared to the wideband radar transmissions, so that even if the bands overlap, the potential interference problem is going to be very slight, and probably nonexistent. We will now assess this problem.

The effective radiated power in the mainbeam of the wideband radar is the product of the peak transmit power (500 w) and antenna gain (40 dB for a 2° beam), which is 67 dBw. The power density (watts per unit area) incident at the target is this quantity divided by $4\mathrm{p}r^{2}$, where r is the range. At the range of 70 km, the power density is thus -41 dBw/m2 . Let us assume that the antenna on board the target has an area of .01 m2, so that if it were pointed directly at the wideband radar, it would receive a power of -61 dBw. Since it is more likely to be pointed elsewhere, the received power is reduced by the sidelobe level. For a sidelobe level of -25 dB, the received power is thus -86 dBw. This power is evenly distributed across the 500 MHz band, so the received power density is -173 dBw/Hz if the bands overlap. This is to be compared to the noise power density in the receiver (the product kTFL) of approximately -200 dBw/Hz. In other words, if the bands overlap, the wideband signal will be about 27 dB above the noise floor. This is probably a conservative estimate.

The bandwidth of the on-board receiver is likely to be only a few hundred kilohertz. Compared to the bandwidth of the wideband transmitter, this is a ratio of less than 1/1000. Therefore, as the transmit signal sweeps across the receive band, its effective duration in the receiver is that fraction of the transmit pulse length. For a target range of 70 km, the transmit pulse length is about 0.25 ms (assuming a duty ratio of 50%), so that the effective duration on receive is probably less than 0.25 ^{m}sec. The reaction time in the receiver is its inverse bandwidth,

which is probably several microseconds. We now have interference that is about 27 dB above the noise floor that lasts for a small fraction of the reaction time, so the net result is that the effective energy within this reaction time is probably not much more than about 10 dB above the noise. Note that the noise itself will generate a spike this high about once every 10,000 reaction times (based on an exponential probability distribution of power), which is comparable to the frequency of occurrence of the interference. Just on this basis, the interference should be harmless. Since the receiver must be designed to operate in a hostile environment, it should be able to accommodate even more severe interference, such as what would happen on those rare occasions when the receive beam happens to point directly at the radar transmitter.

We have assumed a range of 70 km. At shorter ranges, where the potential interference is greater, one can make a case for having the ability to reduce the transmit power. This would be done only at short range, where there is an excess of power, and only if there is a potential interference problem. This means that the wideband transmitter should be designed to operate at different power levels. This is definitely possible with the solid state technology. Since the baseline design consists of several solid state modules, it should be straightforward to utilize any number of these modules in a given test (this is another strong point in favor of the solid state technology over high-power tubes).

This assessment of interference may not satisfy all potential customers. The only conclusive proof would be to conduct a test. Such a test could even be done before a serious design of the wideband radars is undertaken (assuming a representative receiver can be made available). MARK Resources is currently developing very similar wideband test equipment (for Eglin AFB) that could be reconfigured for this test.

3.0 Amplitude Weighting on Transmit

Even if the on-board electronic equipment operates within the tunable band of the wideband radars, it is still possible to avoid interference. For example, since this equipment is likely to be narrowband, there will always be one 500 MHz interval (or two slightly smaller intervals) available within the overall band (the wideband radars can avoid interfering with each other by using different FM slopes and by timing the transmissions). Because the interference is so slight even if the bands overlap, very little separation between the bands is needed to completely suppress the interference. A few megahertz should be sufficient.

An effective way to suppress the out-of-band signals on transmit is to taper the amplitude of the transmit pulse at its edges (such tapering is needed anyhow to suppress range sidelobes, but it is usually implemented on receive). The normal degree of tapering (e.g., Hamming weighting) should provide ample margin in suppressing out-of-band signals even if the on-board antenna happened to point directly at the wideband radar.

Amplitude weighting on transmit is normally not feasible because transmitters like to operate at full power when they are on. This is also the case for individual solid state modules. However, since several modules are needed, there is a very effective way to configure them to produce a variable output power. The modules can be divided into two banks, where a phase shift is applied

A-4

between the banks before their output is summed. Now by varying this phase, the resulting amplitude can be finely controlled anywhere from zero to full value. This can be done very precisely as a function of time across the pulse. The excess power is dumped into a resistive load.

This is yet another strong point in favor of solid state transmitters.

4.0 Extended Range

For both post-mission imaging and real-time display with a wideband radar, a reasonable specification on energy is that the integrated signal-to-noise ratio should be at least 10 dB on a 1 m^2 target at the maximum range of interest [1]. For the baseline design at X-band of 500 w of continuous transmit power (for solid state equipment), a beamwidth of 2° (corresponding to a 1-m antenna), and a combined noise figure and system loss of 2 dB, this specification is applicable for a maximum range of 140 km.

For some applications the wideband radars must operate at longer ranges. One way to extend the maximum range is to provide enough transmit power to satisfy the r^4 law. Thus doubling the maximum range requires an increase in transmit power by a factor of 16 (going from 140 to 225 km is a factor of about seven). At 500 w the transmitter is already the most expensive component in the radar, so by increasing the power by such a large factor we are in effect increasing the cost of the radar by a similar large factor.

There is a much less expensive way to increase the maximum range: we can make the antenna larger. Doubling the width of the antenna increases the two-way gain by the factor of 16. In other words, if we have to operate at double the range, we could double the width of the antenna and operate with the same 500 w of transmit power.

At X-band, a 1-m antenna has a beamwidth of 2° , and the extent of this beam is about 5 km at the range of 140 km. Doubling the antenna width to 2-m will halve beamwidth to 1° and provide the same 5 km coverage at 280 km. The problem with the use of a single antenna in both short- and long-range applications is the narrow extent of the beam at short range. The extent of the 2° beam is about 1 km at the range of 30 km, which is marginal. Reducing the beamwidth by half would not provide adequate coverage at that range.

Since the antenna is relatively inexpensive compared to the total system cost, we could provide an extra antenna to cover the extended range with only a small impact on total system cost. In this case it would be reasonable to use the 1-m antenna from 30 to 140 km and the 2-m antenna from 60 to 280 km. Since these regions overlap, we would have the choice between wider coverage or increased gain in the overlap region. With a 3-m antenna we could extend the coverage to the interval from 90 to 420 km, which would still provide some overlap with that of the 1-m antenna.

There is no need to duplicate the electronic equipment for the multiple antennas. It should be a simple matter to remove the equipment from one antenna and remount it on another (provided this capability is specified in the original design). Each antenna should be equipped with its own

pedestal. There is also another possibility for reflector-type antennas. We can illuminate just the central portion of a large antenna and generate a wider beam. Thus with a single antenna and two (or three) feeds we would have the choice of beamwidths, which could be selected (by manual switching of cables) prior to a mission. The 2-m antenna is probably a good compromise between portability and potential for long-range coverage. If coverage beyond 280 km were needed, it would probably be better to utilize a separate antenna that is tailored for long-range missions.

5.0 Extremely Long Range

A test requirement has been identified for extremely long range, possibly as long as 1200 km, predicated on shore based radars for engagements over the ocean. Although the energy needs at long range can be satisfied by using a sufficiently large antenna (8.6 m in this case), it would be costly to build and operate such a large antenna that is dedicated to just wideband operation. However, there is probably a similar size antenna available (or planned) for conventional narrowband tracking, but at a lower frequency band. Presumably it would be a reflector-type antenna, which means that it could also accommodate the wideband imaging radar electronics (with a separate feed), as long as the reflector surface is of sufficient quality. In other words, both radars can share the same antenna.

By sharing the antennas, there can be only as many wideband radars as tracking radars. At least three are needed for multilateration. However, for such long-range missions we may not more than one, as we discuss next.

6.0 Number of Wideband Radars Required

At least three wideband radars are needed for a multilaterative solution. This will enable individual scatterers on targets to be tracked accurately in three dimensions, for such measurements as vector miss distance and target attitude (the principle of interferometry is an alternative way to perform these measurements as discussed in Section 9, but multiple antennas and receivers are still needed).

Some weapons are designed to hit a specific point on the target, and for such tests only one radar may be needed (assuming that vector miss distance is not an issue if the weapon happens to miss the target). As long as the engagement geometry is reasonable (where the target is not viewed along its axis or at broadside), a single wideband radar will be able to image the target and determine where the intercept occurred. If the damage is slight, then a second radar may be needed to ensure that the damage will be visible to at least one of the radars.

7.0 Ship-Based Wideband Radars

The use of wideband radars on board ships would reduce the range requirement and they could be positioned to provide a near optimum geometry for the multilateration. However, ships are not stable platforms. Without some form of compensation, both the beam position and phase center will move. The beam position should be relatively easy to measure and compensate because the beam is fairly broad. On the other hand, in imaging applications there is usually a requirement to measure and compensate the motion of the antenna phase center to a small fraction of a wavelength. This could be done with ship-board inertial instrumentation, but it would be expensive. Fortunately, it appears that such instrumentation is not needed.

For the anticipated applications of the wideband radars we are interested in only range difference measurements. Since the ship motion affects all objects within the beam in the same way, range differences will be unaffected by the motion. It will be somewhat of a nuisance, however, to deal with the unwanted motion in the motion compensation process.

The wideband radars would still have to be controlled by other tracking radars, which presumably could be shore based. The tracking information must be communicated somehow to the ship based radars.

8.0 Combining Multiple Radars into a Large Array

Normally, radars are designed to be autonomous. One exception is the set of wideband imaging radars that would be slaved to existing tracking radars. But here only relatively little information is needed by the wideband radars in real time: antenna pointing, timing of the pulses and range gate, and possibly infrequent changes in the pulse length and FM slope. Otherwise, there is no coherent relationship between the wideband radars, or with the tracking radars.

For bistatic radars the transmitter and receiver must be coherently related, at least if useful data on targets is to be collected. This concept can be extended to multiple radars, where each is also capable of processing the bistatically reflected signals produced by the others. Although there is more information being processed than would be the case if the radars were to operate in the conventional monostatic mode, it is difficult to predict just how this additional information can result in a better understanding of the target. There is one intriguing possibility, however, as we discuss next.

9.0 Long-Baseline Interferometry

With multiple receivers we can form a long-baseline interferometer to obtain very high angle resolution in the plane of the baseline. This is commonly done in radio astronomy, where experiments have even been conducted with multiple antenna/receiver sets in a worldwide network. In the case of radar, the transmitter and receivers must have a common coherent reference (if we are to utilize phase information), which is difficult to maintain for long baselines. In this regard, it would help if all receivers had line-of-sight visibility with the transmitter so that each could receive and process the transmit waveform.

Let us consider just two receivers separated by d. The resulting interference (voltage) pattern is $\cos(\pi d\theta / \lambda)$, where λ is the wavelength and the angle θ is measured in the plane defined by the baseline. The first nulls in the pattern occur when the argument in the cosine is $\pm \pi / 2$, so that the angular separation of nulls is λ / d. This is also the angular separation of grating lobe peaks. The angular resolution is about half this amount, or $\lambda / 2d$. Suppose we want a resolution of 1 m at 100 km. This translates into a baseline length of 50,000 wavelengths, which is 1.5 km at X-band. This is short enough to have line-of-sight visibility with the transmitter.

The close spacing of grating lobes, only about twice the size of the resolution cell, is undesirable when the target extends over several resolution cells. Since the target is presumably also being resolved in range and Doppler, we can unscramble these angle ambiguities for known targets, but this places an extra burden on the data processing.

We can increase the spacing of the grating lobes, and still keep the same resolution, by increasing the number of receivers. For N receivers equally spaced by d along a baseline, the grating lobes are still spaced by λ / d, but the resolution is approximately λ / Nd. In other words, for N receivers the grating lobes will be spaced by about N resolution cells. To avoid ambiguity problems entirely, the spacing of grating lobes would have to be greater than the target extent. Thus for 1 m resolution on a 10 m target we would need ten receivers.

Considering that a similar number of receivers is needed to obtain the same performance in the orthogonal direction, eliminating the grating lobe problem comes at a high price. It would be far cheaper to accept some angle ambiguities, which could then be unscrambled in the data processing (the extra effort should be much less than what is required for the pulse compression, motion compensation, and tracking of scatterers). A reasonable compromise between number of receivers and extra effort might be to have three receivers along a baseline plus two more in the orthogonal direction.

The interferometer can be wideband, and as with multiple wideband radars operating in a multilaterative configuration, it can be slaved to existing tracking radars to avoid duplicating this costly function. The hardware for both configurations is similar, except only one transmitter is needed for the interferometer, and the multiple receivers must all be phase coherent with each other and the single transmitter.

Under ideal conditions, this wideband interferometer should be capable of measuring scatterer positions to a precision of a few centimeters in three dimensions. A similar precision can be obtained with three or more wideband radars operating in a multilaterative configuration. However, the interferometer has several advantages over the multilaterative configuration: (1) true resolution is achieved in four dimensions instead of two, (2) it does not suffer any geometric dilution of precision, (3) it does not have a scatterer association problem, and (4) it operates in a single band. On the other hand, it has certain disadvantages: (1) more computation is required to form the beams, (2) the antenna locations must be accurately surveyed (or calibrated), (3) it depends much more on a stable atmosphere (and stable antennas), and (4) resolution is degraded in the vertical plane at low elevation angles (see Section 11). Both configurations are theoretically capable of producing the same measurements of interest, such as target attitude, miss

distance, damage assessment, and deployment. The overall cost, including hardware, software development, maintenance, and labor, should be similar in either case.

Because the hardware is so similar for either case, there is a very low-risk approach to decide which concept is best (or even if the interferometer is viable). Three wideband radars should be constructed so that they can operate in either a multilaterative configuration or as an interferometer. Experiments can then be conducted in either configuration, which should provide ample data to make a decision on which way to proceed. Additional radars or receivers can then be purchased to satisfy an overall performance requirement. Since the transmitters are probably the highest cost item, they should be initially of low power in order to minimize the overall cost.

A strong case can be made for designing the new wideband instrumentation system to accommodate both modes of operation, multilaterative radar as well as interferometer, assuming the latter is viable. In Section 1 we were concerned with selection of the frequency band to avoid possible conflicts with on-board equipment. It is highly desirable to operate at a frequency band where solid state transmitter modules are available, which may force us to operate in a potentially conflicting band. Since the bandwidth of the on-board equipment is likely to be very narrow, we will always be able to find a non-interfering interval of 500 MHz in the overall tunable band (of 1 GHz). Weighting on transmit, as discussed in Section 3, can be used to suppress the out-of-band interference, if necessary. Limiting the instrumentation system to a single 500 MHz band would favor the interferometer mode over the multilaterative radar mode (when there is a potential interference problem). On the other hand, the interferometer would be more difficult to implement in a ship based system.

A related subject is the MSTS concept, which is reviewed in Section 20.

10.0 <u>Making an Interferometer Work</u>

Normally, a nonhomogeneous and scintillating atmosphere will limit the performance of an interferometer. However, as long as one scatterer can be resolved on the target, we should be able to compensate the motion of that scatterer in all receive channels. This will automatically compensate for any time-varying atmospheric effects, and it will allow us to normalize the amplitude among all channels. All measurements, including those in angle, can now be made with respect to the reference scatterer.

With a simple target, it may be possible to perform this motion compensation with only Doppler resolution. However, for most targets of interest we will also need high resolution in range. Thus the initial set of wideband radars/receivers would be ideal for conducting tests on how well atmospheric effects can be compensated. Data should be collected under a variety of atmospheric conditions.

It is theoretically possible to use the existing MOTR systems to collect data for interferometric processing. However, software modifications would be required. One system would operate in a receive-only mode, slaved to the other. The former would also have to establish a track file on the line-of-sight transmissions of the latter, which could be received in the antenna sidelobes.

Since we ought to be able to compensate for the variable atmosphere, we should also be able to also compensate for the motion of each ship. If we had interferometer data collected by land based radars, we could simulate the ship motion to determine how difficult it would be to compensate for that motion.

A wideband interferometer has the potential for true resolution in four dimensions: range, Doppler, and two angles. While only two dimensions (range and Doppler) would be used for the initial motion compensation, thereafter we could process simultaneously in all four dimensions to resolve scatterers that may otherwise be unresolvable. The question is, just how should this be done? It is clear that some type of expert system would have to be employed.

If the resolution in angle is relatively poor compared to range and Doppler, perhaps the only use it will be is to measure the angular position of scatterers that are already resolved in one of the other dimensions. In this case, the processing should be straightforward.

11.0 Degradation of Resolution for an Interferometer

Let D be the length of the baseline and q the angle between the baseline and line of sight. The resolution in angle is given by $\lambda / (D \sin q)$, where the angle is measured in the plane defined by the baseline and line of sight. The best resolution in angle is obtained when the line of sight is perpendicular to the baseline ($q = 90^{\circ}$).

The interferometer principle works best when the engagement is overhead, because orthogonal baselines will provide the highest resolution in the two angles. When the engagement is viewed at lower elevation angles, the resolution in the elevation plane will be degraded unless the baseline in that plane can be extended (or tilted) accordingly. Eventually, however, it will be very difficult to obtain any usable resolution at low elevation angles (for an elevation angle of 5°, the baseline would have to be 11.5 times longer in order to have the same resolution as an overhead engagement).

Operating at low elevation angles degrades resolution in one angle but not the other, so that, depending on the engagement, the resulting resolution in angle may still be very useful. For example, for a missile flying nearly horizontally we do not need any resolution in the vertical plane.

12.0 Array Thinning

The thinning of elements is a way to reduce the cost of an array antenna, while still maintaining the same beamwidth. It is also a way to reduce the concentration of dissipated heat, which becomes important at the higher frequencies where the elements are closely spaced. The price we pay is an increase in the sidelobe level.

Let us assume that N isotropic elements are randomly placed across the array face, and the power associated with each element is the same. The radiated power at the mainbeam peak will be proportional to N^2, assuming that all elements are in phase, while the average power radiated in other directions will be proportional to N. Therefore, the average sidelobe level will be 1/N on a power basis for this case. To achieve an average sidelobe level of -30 dB, for example, we should have at least 1000 elements. Some of the sidelobes will be higher than this average level, of course. We can expect peak levels of approximately 4 dB higher than the average level.

To illustrate this phenomenon we have randomly placed 1000 elements on a rectangular grid within a circular aperture as shown in Figure A-1[1]. The corresponding pattern, which has a beamwidth of about 1°, is shown in Figure A-2 (a cosine-shaped power pattern for each element is assumed).

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[1] For a filled array on a rectangular grid, the element spacing cannot exceed $\lambda / (1 + \sin q_m)$, where q_m is the maximum scan angle from broadside, in order to prevent grating lobes [2]. The maximum spacing of elements for a $\pm 60^{\circ}$ scan is thus $.536\lambda$, which is the spacing used here.
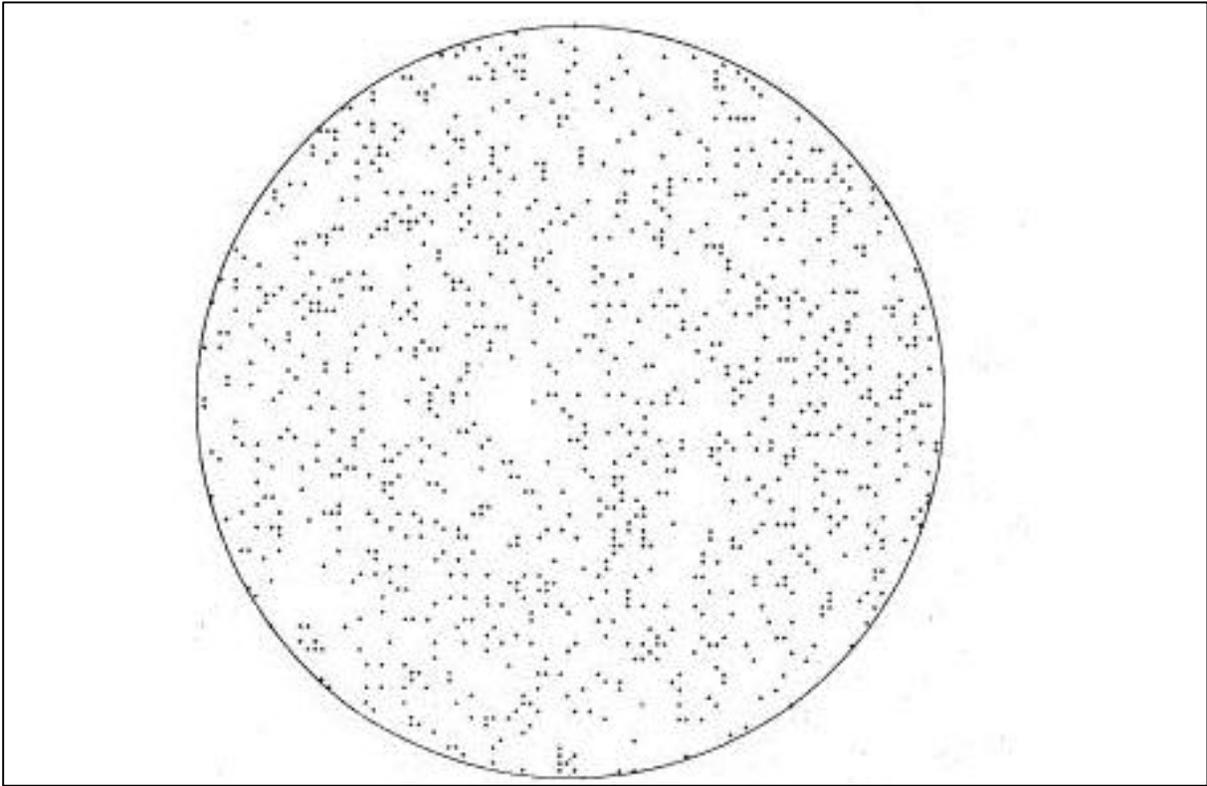
Figure A-1. Uniform Distribution of Elements within a Circular Aperture.
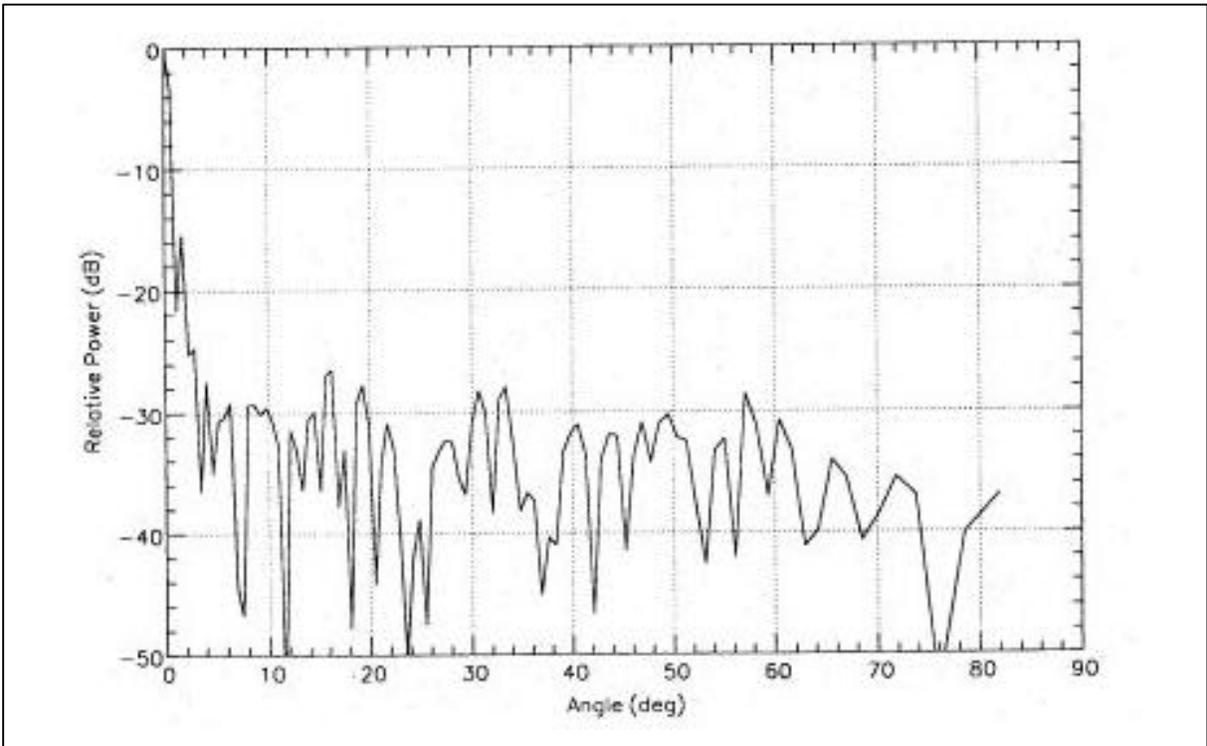

Figure A-2. Antenna Pattern for Element Distribution in Figure A-1.

Neglecting those close-in, most sidelobes are below -30 dB, while a few are about 4 dB higher, as expected (note that the detailed sidelobe structure will be different in different planes). If the same grid were completely filled, there would be 7850 elements, so only about 13% of the grid locations are occupied for this example.

The near sidelobes are due to the fact that the elements are weighted equally, which would produce a first sidelobe at -17 dB for a filled array. Normally, one employs amplitude or phase weighting to suppress near sidelobes. However, we also have another option for thinned arrays. We can concentrate the elements more in the center of the aperture than at the edges. This will allow us to weight the elements equally, which is advantageous for an active array because the full potential power (N times the power in each element) can be utilized. For example, in Figure A-3 we show a random placement of elements according to a two-dimensional Gaussian distribution, where the aperture edge is at two standard deviations. The resulting antenna pattern is shown in Figure A-4. In comparison with Figure A-2, we see that the mainbeam is well formed and the first two sidelobes have been suppressed. The beamwidth has increased by approximately 30%, which is typical for a weighted aperture.
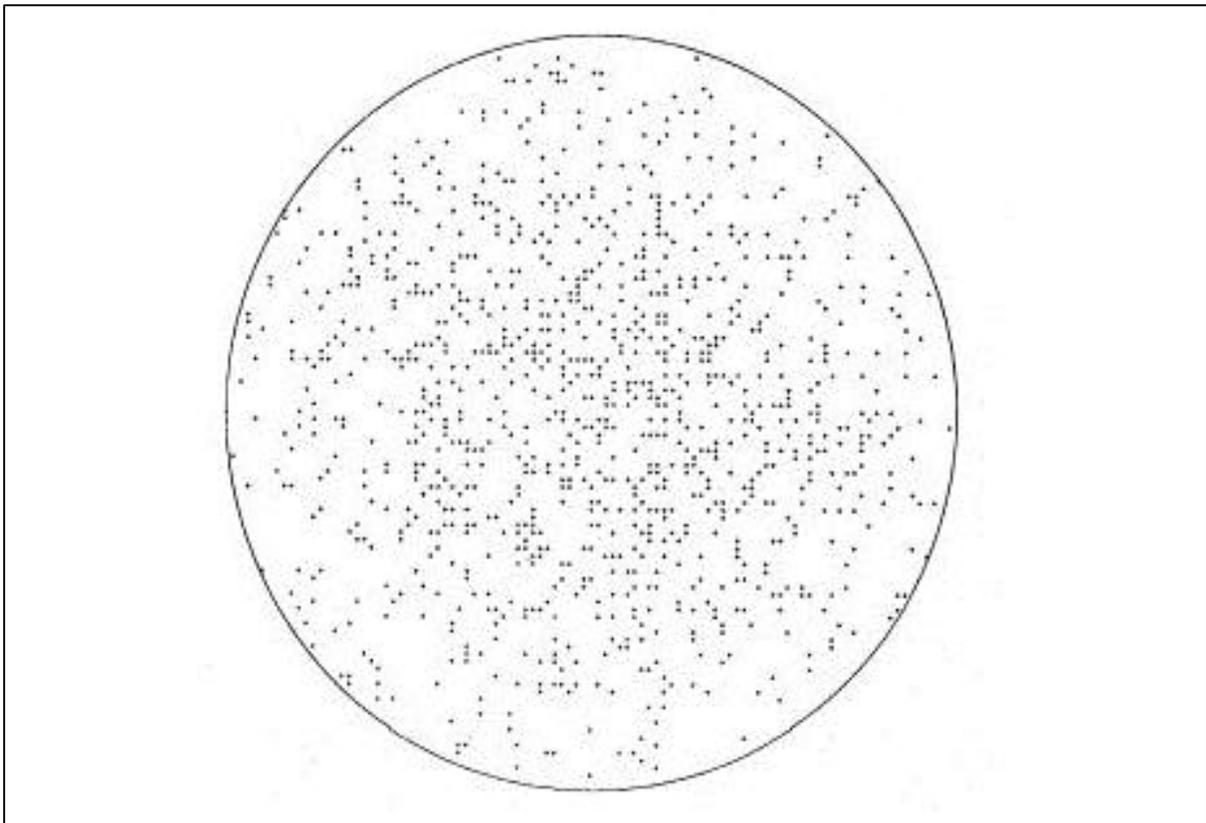

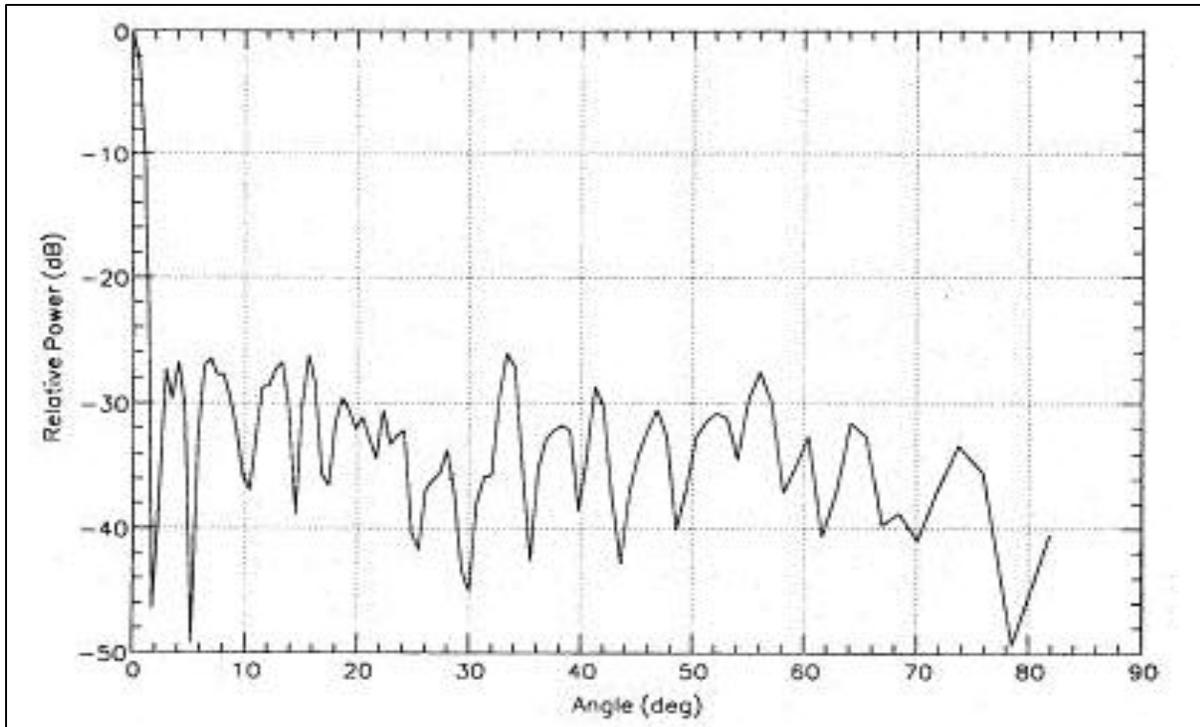Figure A-3. Concentration of Elements in Center of Aperture.

Figure A-4. Antenna Pattern for Element Distribution in Figure A-3.

In the above example, there are elements at approximately 13% of the grid locations within the circular aperture. If we were to design for -30 dB peak sidelobes instead of an average level of that amount, the number of elements would have to be increased by a factor of 2.5, which means that the array would be about 32% filled. Array thinning is beginning to lose its appeal. For any further decrease in the sidelobe level it would be better to work with a filled aperture.

Array thinning is especially advantageous for narrow beams, as long as the sidelobe requirement is modest. For example, we can double the width of the above aperture to halve the beamwidth, and with the same number of elements we can maintain the same average sidelobe level. Thus we have reduced the percentage of occupied grid locations by a factor of four. On the other hand, if we reduce the width of the aperature to increase the beamwidth, we will increase the percentage of occupied grid locations. Eventually, the grid becomes fully occupied. For 1000 total elements this occurs when the aperture is about 36 elements wide, which corresponds to a beamwidth of about $3°$.

For thinned arrays the effective radiated power and average sidelobe level are dependent on the number of elements, while the beamwidth is a function of the aperture size. This gives one considerable flexibility to design specific characteristics into the pattern the other hand, if we reduce the width of the aperture to increase the beamwidth, we will increase the percentage of occupied grid locations.

13.0 Electronic Scan with Wideband Waveforms

The electronic scan of a phased array (from broadside) is limited for wideband signals. A conservative rule of thumb is that the depth of the antenna along the line of sight should not be greater than about twice the range resolution of the waveform. Thus for a 500 MHz bandwidth waveform (one-foot resolution) and an antenna width of 12 feet, the scan is limited to about $\sin^{-1}(1/6) \approx 10°$ (the derivation in [3] allows the scan to be 50% greater by utilizing a modes amount of superresolution). As long as the antenna can be mechanically pointed at the center of the engagement, we can operate at the full 500 MHz bandwidth within $\pm 10°$ of the boresight axis, and with degraded resolution outside that cone (330 MHz at $15°$, 250 MHz at $20°$, 200 MHz at $25°$, and so on). This should be more than adequate for practically all engagements of interest (provided the radar has the ability to utilize different bandwidths).

Nevertheless, there appears to be some interest in the use of the widest bandwidth at large scan angles. This can be done with true delay steering, but this is an expensive solution. A much more practical solution is discussed next.

14.0 Segmented Linear-FM Waveforms

There are two general classes of wideband waveforms that can be used for imaging targets: the linear-FM and stepped-frequency waveforms. There are advantages and disadvantages for each. The spectrum of the linear-FM waveform is filled, so the only range ambiguity is that of the repetition period. The spectrum of the stepped-frequency waveform exists at discrete lines, so there are range (delay) ambiguities at the inverse of the frequency step. For aircraft targets the waveform should be repeated rapidly enough to accommodate the broadband modulation of rotating blades on aircraft, and this is far easier with the linear-FM waveform. On the other hand, the stepped-frequency waveform is entirely compatible with array antennas because the phase shifters can be reset between pulses (frequency steps).

The principal problem with the linear-FM waveform is that it is basically incompatible with large array-type antennas that utilize phase shifting for the scan, as discussed above. Although the stepped-frequency waveform is compatible with such antennas, it is not well suited for the imaging of aircraft because of its relatively slow repetition rate. However, there is a compromise. We can synthesize the linear-FM waveform in segments, where the bandwidth of each segment is small enough to allow sufficient off-broadside scanning of the array and where the number of segments is small enough to allow a sufficiently high repetition rate of the waveform to accommodate aircraft targets (20 kHz would be ideal, but 10 kHz is acceptable). The phase shifters on the array will be reset between waveform segments.

The FM sweep across the segments should be contiguous (i.e., no gaps in the spectrum). For five segments of 100 MHz each, we could extend the above 10R scan limit by the same factor of five, which should be more than adequate for any application. Both the number of segments and the segment bandwidth should be adjustable according to the scan angle and the desired resolution.

The segmented linear-FM waveform is entirely practical. In fact, it is currently being investigated by NRL in an effort to add a wideband capability to an existing phased array system [4]. MARK Resources has even examined some of their data. For example, in Figure A-5 we show the residual phase across a 400 MHz band after a waveform consisting of ten 40 MHz segments has been demodulated. The segment boundaries at every 200 samples in Figure A-5 are barely discernible, and the very low phase residual will result in negligible range sidelobes. We have observed a slight jitter from one repetition of the waveform to the next, which should be corrected by better synchronizing the A/D converter with the transmit trigger.
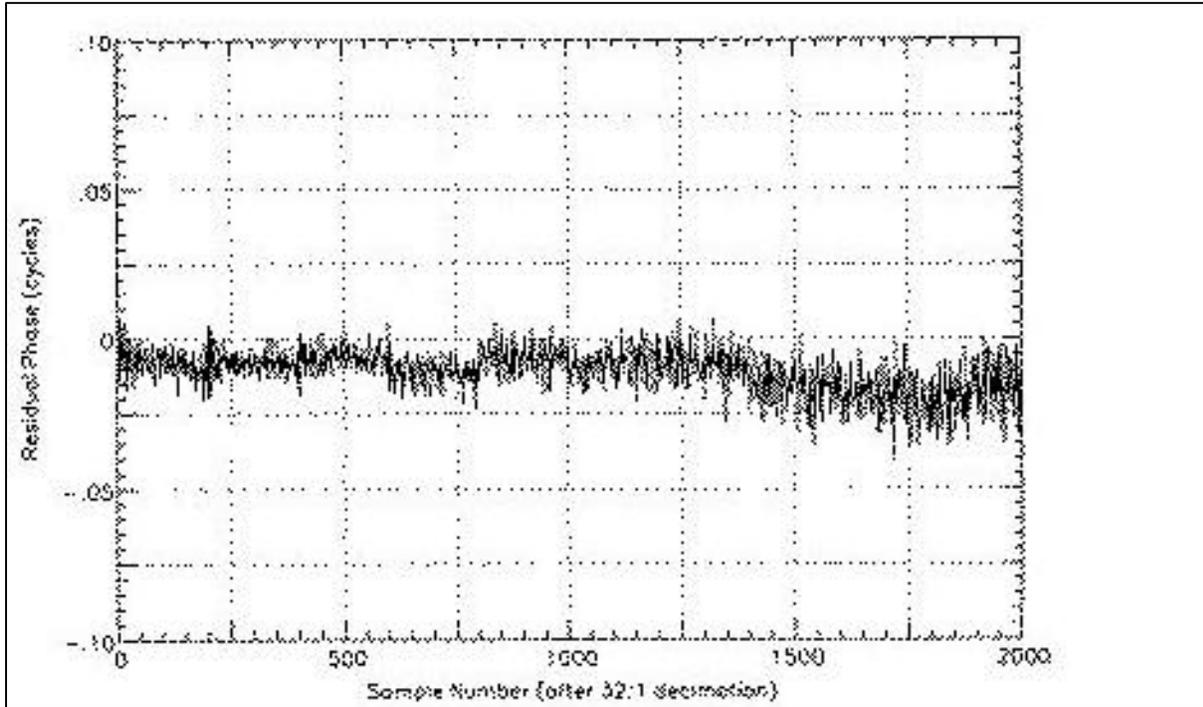

Figure A-5. Residual Phase After Demodulation of Segmented Waveform.

15.0 Segmented Linear-FM Burst

The full waveform should be repeated at the rate of at least 10 kHz in order to accommodate aircraft. If each linear-FM segment is transmitted after the previous segment is received, then the range will be limited to only a few kilometers. In order to extend the range, all waveform segments should be transmitted in a burst before any are received. The transmitter should pause just long enough to allow the antenna phase shifters to be reset. This burst-mode operation also requires an adjustment of the receiver passband from one waveform segment to the next.

16.0 Upgrading the MOTR System with Segmented Linear FM

There is a plan to upgrade the MOTR system for wideband operation. Since its antenna is a phased array, the logical choice of waveform is the segmented linear FM. But there is a potential problem of a narrow range window due to the combination of a low duty ratio of the transmitter (a few percent) and a low sampling rate of the A/D converter (6 MHz).

With stretch processing, a delay difference of Δt will appear as a difference in frequency of $\Delta f = k \Delta t$, where k is the slope of the linear FM. The maximum frequency difference that can be accommodated is the IF bandwidth after demodulation but prior to A/D conversion, which we will designate as B_i. Writing k = B/T, where B and T are the bandwidth and duration of the sweep for one segment, we obtain the limit on the width of the processing window in delay of $\Delta t = B_i T / B$. For B_i = 5 MHz, T = 20 msec, and B = 100 MHz, the maximum width that can be accommodated is just 1 msec (150 m).

17.0 Active Arrays

For a conventional phased array antenna, transmit power is distributed to all elements where phase shifts are applied to steer the beam. The returns are superimposed (after the phase shifts) and processed in the receiver.

There is much activity today in the development of active array antennas, where each array element contains a low power transmitter and a low-noise front end receiver, in addition to a phase shifter. In this form the active array is functionally the same as a conventional phased array. A single beam is created on both transmit and receive, and the beam is steered by controlling the element phases. An active array can operate with a high duty ratio, whereas a conventional phased array must operate with a low duty ratio. The average power can be much higher for an active array.

The active array also has the potential for growth into a much more capable antenna. By including a complete receiver (up to the A/D converter) at each element, instead of just the front end of the receiver, it will be possible to form multiple beams simultaneously on receive. This is usually called digital beamforming, which is discussed next. Because of the added expense, it is not a viable candidate for a test range radar, at least in the near future.

18.0 Digital Beamforming

If there is a receiver at each element in an antenna array, then multiple beams can be formed simultaneously on receive after the mission is completed. This will allow us to dwell essentially continuously on all objects within the illuminated sector. One problem is the high overall data rate and high data volume, both of which are especially high for wideband operation. Let us first examine the situation at a single element. The effective data rate is the number of samples per pulse times the pulse repetition rate. For 7000 samples per pulse (a range window of 7000 ft at one-foot resolution) and a pulse repetition rate of 1 kHz, the effective data rate is thus 7 Msamp/sec, or 14 Mbytes/sec (for two bytes of raw I/Q data per sample). For a one-minute mission, this is a total of almost 1 Gbyte of data. Both the data rate and volume can be handled in modern computer memory, and the results can be written to a single disk, almost in real time.

The above numbers get multiplied by the number of array elements, assuming there is a receiver at each element. One computer can accommodate a few elements, but not many because of the finite access time, perhaps only two with the technology available today. Therefore, if we were to have a receiver at each of 7850 elements in a completely filled array, we would need about 4000 high-performance computers just for the recording of data, which would cost tens of millions of dollars. Even for a thinned array of 1000 elements, we would need 500 computers, which would still cost several million dollars. For the tracking of multiple objects in a test range environment, there is no need for each array element to be equipped with a receiver. We can partition the aperture into subarrays, where the elements within one subarray are integrated into a single receiver. The digital beamforming will now be confined to the sector defined by the pattern of a subarray. For a subarray consisting of 10x10 grid elements, for example, we should be able to form multiple beams within a sector of about $10°$ (the whole sector can be phase steered in real time). We have now reduced the number of receivers from 7850 to 80, which will have a significant impact on the cost of the computers (probably less than one million dollars).

19.0 Active Array for Multiple Object Tracker

Prior to acquisition, the transmit beam of an active array must illuminate the entire surveillance sector. This can be done with sequential beams, but if we are to take advantage of digital beamforming on receive, the entire surveillance sector must be illuminated continuously. If this sector is N times the area of the narrowest beam that can be formed, then the effective gain of the antenna is reduced by the same factor of N. However, we can make up for this loss by forming N beams simultaneously on receive, rather than to visit the N positions sequentially. This way the entire energy available in a given dwell can be utilized by all N beams. In other words, compared to a sequential scan, we have 1/Nth of the gain on transmit in each beam position but N times the energy on receive. The detection performance will be nearly the same in either case.

If multiple objects are already in track, it is possible (in theory) to shape the transmit beam so that energy is directed only at the objects. This way we can avoid wasting energy in those beam positions that are empty. The problem is that the complex weights associated with each element are now much more difficult to compute than what is required to electronically steer a single beam (or a set of contiguous beams). Moreover, the computation has to be performed often enough to keep up with the changing target environment, which can be especially demanding at short range.

The problem can be simplified by partitioning the array into subarrays, just as we did on the receive end. Let M be the number of subarrays, which cannot be less than the number of resolved objects in track. We will have to derive the M complex weights to form the beams, presumably by some optimization procedure, and it must be done in real time. We assume that the computation is essentially equivalent to solving a set of M simultaneous equations involving M unknowns. Even though the problem should be well behaved (not close to singular), single precision arithmetic will limit M to no more than about 50, and probably less [5]. Double precision would be impractical.

Inversion of a matrix of real elements can be done in about $8M^3$ clock cycles in a modern PC-based digital signal processor with a 40 MHz clock [6]. Solving simultaneous equations requires about half as much work, but the weights are complex, which requires about four times as much work as real weights. We will assume the resulting computation effort is therefore about $16M^3$ clock cycles. The computation time for 25 weights is approximately 6 ms, so that the weights could be updated at a rate of about 160 Hz, which should be more than adequate in any application. However, as we increase the number of weights, the update rate rapidly decreases. For 30 weights the update rate is about 90 Hz, for 35 weights it is less than 60 Hz, and for 40 weights it is less than 40 Hz. Based on the update rate, the practical limit is probably about 35 weights, which is also consistent with the single precision limit. We could use a more capable signal processor to increase the update rate for a large number of weights, and we may also be able to apportion the computation into multiple devices. However, eventually we would have to use double precision, which is counterproductive.

We conclude that the use of an active array for illuminating multiple objects simultaneously is entirely practical, as long as the antenna is partitioned into subarrays, and the number of subarrays does not exceed about 35. This will limit the number of resolvable objects in track to also about 35. Of course, the radar can always track more objects, but only in a time-sharing mode.

The partitioning of the antenna does not have to be the same on both transmit and receive, although it may simplify some of the beam steering computations if it is. Moreover, array thinning is also possible with both digital beamforming and active arrays, and the positions of the thinned elements need not be the same on both transmit and receive. This means that some grid elements could be devoted to transmit and others to receive, which would eliminate the need for rapid switching (at every array element) between these functions.

20.0 Review of the MSTS Concept

Several years ago the Army considered developing the MSTS system. On paper it consisted of a conventional phased array radar plus a very long linear array, composed of about 100 elements, which was intended to be used in a receive-only mode. The spacing of elements (about 1 m) in this horizontal receive array was far more than the amount needed to avoid grating lobes, but since only one grating lobe interval was illuminated by the transmit antenna, the multiple lobes were effectively suppressed. The long array provided resolution in azimuth of about 0.2 mrad (at Ku-band). At the range of 5 km the azimuth resolution was comparable to the range resolution of 1 m. There was also a short vertical array (about 6 m) to provide coarse resolution in elevation.

This system was not developed, presumably because it was too expensive. Most of the cost was associated with the receive array, including electronics and data processing. This array acts as a digital beamformer, so a complete receiver had to be replicated at each element. In this report we have investigated the use of array thinning and partitioning to reduce cost, but neither is applicable to the MSTS concept (the former is practical only when there are at least about 1000 elements, and the latter is feasible only when the sector illuminated by the transmit antenna is much less than the spacing of grating lobes).

In the meantime, however, much has transpired to reduce the cost of the electronics and data processing. The MMIC technology has matured considerably and digital processors have become very affordable. Moreover, rather than send raw A/D converter data to a central computer for processing, it is now feasible to equip every receiver with a very powerful digital signal processor (at a cost of about $2,000 each, as described in [6]). By pulse compressing the signal first and then selecting only those intervals containing targets, we reduce the data rate to the central computer by at least an order of magnitude.

21.0 Technology Considerations

For some radars it will be much easier to upgrade performance than for others. On the one hand, for the wideband imaging radars (that are slaved to other tracking radars) it will be relatively inexpensive to increase both the power and resolution bandwidth in existing units, and to change the antennas. Very little re-engineering is needed, and the cost of the new or additional components (with the exception of the transmitter modules) is small compared to the cost of the original system. Therefore, it is practical to design such radars to meet the requirements of near-term testing. Very little effort and cost would be needed to upgrade these radars to meet a more stressing future requirement.

On the other hand, such improvements or changes would be very difficult and costly for practically all other types of radar (and only for a reflector antenna would it be feasible to consider changing the antenna). Therefore, this inflexibility to change has to be factored into the original design of the system. In order to postpone obsolescence, the system must be designed to meet not only the requirements of near-term testing, but also the anticipated requirements of future testing. In essence, such radars must be over designed according to current requirements.

References

1. Mitchell, et al., "Applications of Radar Imaging to High-Altitude Measurements," MARK Resources Report 381-49 (Phase II), Nov. 1997, Section 2.

2. . Skolnik (ed.), Radar Handbook (Mc-Graw-Hill, 1970), Chapter 11.

3. Mitchell, et al., "Applications of Radar Imaging to High-Altitude Measurements," MARK Resources Report 377-3 (Phase I), Jan. 1995, Section 6.

4. Contact Mike Steiner at NRL, 202-404-1886.

5. Press, et al., Numerical Recipes (Cambridge University Press, 1986), Chapter 2.

6. ADSP-21000 Family Applications Handbook, Volume 1 (Analog Devices Inc., 1995), p. 81.

APPENDIX B

RATIONALE FOR THE ROADMAP

Appendix B

Rationale For the Roadmap

The Radar Roadmap is a visionary guidance document, -- a statement of instrumentation radar requirements from the technical community. It is a look 10, 20 ,and even 30 years into the future.

By instrumentation radar we mean radars specifically designed for tracking objects under test (e.g., aircraft, missiles, drop objects, deployed objects, etc.). Included would be low-power FPS-16 class single-object trackers, high-power MIPIR class radars, phased array multiple-object trackers, CW radars (e.g., velocimeters and Weibel radars), and special purpose tracking radars (e.g., the KREMS radars at Kwajelein Missile Range). We have not included surveillance radars (although they might be used in training exercises or to control air space at test ranges), static test range Radar Cross Section measuring radars, weapons system radars, or radars designed specifically for the intelligence community.

We considered all ranges involved in test and evaluation (T&E), including developmental testing (DT) and operational testing (OT). We also considered all training ranges that are using radar.   In the process of visiting (or calling) each range and discussing its mission, we encountered a variety of activities which, although sometimes a substantial part of a range's workload, do not fit into our consideration of test and training ranges. These activities include operational space lifting, deep space tracking, space object identification, foreign missile launch tracking, and static range radar signature measurements.

When doing the Radar Roadmap study, we chose not to try to find documented requirements 10, 20, and 30 years into the future. We are usually lucky to be able to find documented requirements 5 years in the future!   Instead, we relied mostly on the radar people at each of the ranges to describe their requirements. These derivative requirements, as we call them, consist of extrapolating the kinds of testing the range is currently doing, and factoring in what they have been told will be happening in the future. We also talked to the Ballistic Missile Defense Organization (BMDO) because several ranges cited them as the source of future requirements.

It will be noted that the Radar Roadmap contains neither a timeline nor a cost benefit analysis. We feel it would be inappropriate to do so. The Roadmap is intended to be a visionary document from the technical community, -- a composite of the radar requirements of all the test and training ranges. The timeline and cost benefit analysis, by contrast, are management tools which each range must apply individually in its own planning process. In other words, the Radar Roadmap is not a development plan for a specific range, but a document which we hope will assist them in putting together such a plan. Further, the Roadmap is not a management document, a funding document, a Base Realignment and Closure (BRAC) plan, or a document which binds the ranges in any way.

APPENDIX C

LIST OF RANGES CONTACTED OR VISITED

Appendix C

List of Ranges Contacted or Visited

1.0 Visited

We visited, briefed and held discussions at the following test and training ranges:

- U. S. Army White Sands Missile Range, NM
- Naval Air Warfare Center, Weapons Division, Point Mugu, CA
- U.S. Army Electronic Proving Ground, Fort Huachuca, AZ
- Air Force Development Test Center, Eglin AFB, FL
- Naval Air Warfare Center, Aircraft Division, Patuxent River, MD
- Aberdeen Test Center, Aberdeen Proving Ground, MD
- NASA Wallops Island Flight Facility, VA
- Yuma Proving Ground, AZ
- 30th Space Wing, Vandenberg AFB, CA
- NASA Dryden Flight Research Center, CA
- Air Force Flight Test Center, Edwards AFB, CA
- Naval Air Warfare Center, Weapons Division, China Lake, CA
- Atlantic Fleet Weapons Training Facility, Roosevelt Roads, PR
- 45th Space Wing, Patrick AFB, FL
- Air Warfare Center, Nellis AFB, NV
- The Tonopah Test Range, NV
- U.S. Army Dugway Proving Ground, UT
- Utah Test and Training Range, Hill AFB, UT
- Kwajalein Missile Range, Republic of the Marshall Islands
- Pacific Missile Range Facility (PMRF), Kekaha, HI

2.0 Briefings and Discussions

We also visited, briefed and held discussions at the following:

- Electronic Trajectory Measurements Group (ETMG) meeting at Eglin AFB, FL
- Headquarters, U.S. Army Test and Evaluation Command (TECOM), APG, MD
- Ballistic Missile Defense Organization (BMDO), Crystal City, VA
- Executive Committee of the Range Commanders Council (RCC/EC) meeting at Nellis AFB, NV

3.0 <u>Contacted</u>

We contacted but did not visit the following:

- Atlantic Undersea Test and Evaluation Center (AUTEC), West Palm Beach, FL
- Arnold Engineering Development Center, Tullahoma, TN
- Air Defense Artillery Test Directorate, Fort Bliss, TX
- Naval Undersea Warfare Center, Keyport, WA
- Southern California Offshore Range Environment (SCORE), San Diego, CA
- 46th Test Group, Holloman AFB, NM
- Barry M. Goldwater Air Force Range, Luke AFB, AZ