

A DISCRETE ADDRESS BEACON SYSTEM

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Summary. The two most basic requirements for air traffic control are surveillance and communications. The surveillance system in use today is the Air Traffic Control Radar Beacon System. It is based on World War II technology and is experiencing severe difficulties as the number of aircraft carrying transponders increases. This paper outlines the present FAA program to develop a new surveillance system which will eliminate the problems, will be compatible with the existing system and will also provide a digital data-link for collision avoidance and air traffic control purposes.

Introduction. One doesn't usually associate the word "telemetry" with air traffic control unless referring to special instrumentation used to collect flight test data on some new navigation or guidance system. However, as the FAA is now proceeding to upgrade the capacity and performance of the ATC system to meet the expected growth in aircraft activity we are engaged in developing a major telemetry system.

The functions of ATC are shown in Figure 1. The pilot files a flight plan and is expected to navigate himself along the agreed route using the extensive ground network of VOR's and DME's operated by the FAA. The military also use TACAN for navigation and a combined VOR, DME and TACAN facility is called a VORTAC. In the early days---until the mid-1950's---pilots reported their position and progress, as determined by the navigation system, to the ground controllers by voice radio. To allow for error and communication delays the aircraft separations had to be quite large. Today there is separate surveillance determination on the ground---first radar and now secondary radar or beacon, with FAA terminology ATCRBS, for Air Traffic Control Radar Beacon System. Radar has many problems including ground clutter, weather clutter and the generally poor echos from small general aviation aircraft. Beacon is better, albeit at the expense of requiring the necessary transponder in the aircraft.

Today surveillance from the ground is necessary if the system is to accommodate more aircraft at smaller spacing. Thus the present ATCRBS is a basic and important tool. The ATCRBS is a form of telemetry, the ground based system sends out interrogations at 1030 MHz and the airborne equipment responds at 1090 MHz. These are between 80,000 and 100,000 airborne equipments, called transponders, in the U. S. civil and military fleet.

There are 291 civil interrogators, over 500 military interrogators and many high powered special purpose test facilities that people don't bother to register, all working at the same frequency. The system is relatively undisciplined in that pilots of uncontrolled aircraft can turn their transponders on or off pretty much as they choose and although there are several comprehensive and reasonable specifications for the characteristics of the transponders, the manufacturers are not required to meet these specifications. The maintenance and calibration of the general aviation transponders also frequently leaves much to be desired. Even though this system seems chaotic it is in fact a very important telemetry system and it works better than one might expect.

Figure 2 indicates the fundamentals of the system. The interrogator antenna is mechanically rotated and has a horizontal aperture of 28 feet in the FAA versions. The vertical dimension is slightly over one wavelength which leads to multipath and lobing problems. The 28 foot dimension and the 1 foot wavelength provides an azimuthal beamwidth of about 2.5° . The effective beamwidth is somewhat wider. As the antenna beam swings around, it sends out the interrogations shown in the lower part of the figure. The interrogations are at 1030 MHz and use 0.8 micro-second pulses as shown in Figure 3. For civil applications we use Mode A and Mode C interrogations. The Mode A interrogations have a spacing of 8 micro-seconds between P_1 and P_3 , P_1 and P_3 are transmitted via the rotating directive antenna. P_2 is transmitted from an antenna with a pattern which is omni-directional in azimuth. This is the Side-lobe Suppression Pulse and its functions will be described below. A transponder which decodes a valid Mode A interrogation will respond with the transmission shown in the next slide. The transmission uses 0.45 micro-second pulses spaced 1.45 micro-seconds leading edge to leading edge. There are the two framing pulses spaced 20.3 usec apart. Between these two framing pulses, there are 13 positions where pulses could occur. The middle (or seventh) of these pulses is called the "X" pulse and is not presently used except for special military purposes involving unmanned airborne vehicles. The remaining twelve pulses can be used in various combinations. It is clear that there are 2^{12} or 4096 various combinations which can be transmitted. Modern transponders which are designed so that they can transmit any of these codes are called "4096 transponders" in contra-distinction to earlier models which could only transmit 64 codes. The control panel of the transponder has four octal thumbwheel switches allowing the pilot to set up one of these 4096 codes. When a Mode A (called Mode 3 in military terminology) is decoded, the transponder interprets this to mean "Who are you?" and responds with the framing pulses and the code pulses appropriate to the thumbwheel switch setting. The extra pulse shown at 4.35 usec after the second framing pulse is called the Special Position Identification or SPI pulse. If the controller tells the pilot to "Sqawk Ident" the pilot pushes a button on the transponder control panel. For the next 20 seconds the transponder adds this pulse to its normal response when answering a Mode A interrogation. The controller's displays are designed so that they exhibit a very distinctive target mark when this signal is received. This permits

the controller to rapidly identify the position of any particular aircraft. Figure 3 also shows a Mode C interrogation and aircraft response P_1 and P_3 are 21 usec apart as opposed to the 8 usec of Mod; 3/A. The transponder interprets this as “How high are you?” and if the aircraft is equipped with an encoding altimeter it sends back the framing pulses and uses the information pulses to transmit barometric altitude using a modified Grey code. The important point to be made is that although this all may seem a little crude it is a true telemetry system and is the most widely used and important telemetry system we have today. It is based on World War II technology and as more and more aircraft are equipped with transponders and as more and more interrogators are installed on the ground, it begins to show some serious defects. The FAA response over the years has been to put patches over the defects. The system now has more patches than anything else and we are running out of places to sew on new patches. Discussed below are some of the problems and the fixes which have been implemented.

Side Lobe Suppression. Figure 4 diagrams one serious defect that cropped up early . There is some energy radiated in the side and back lobes of the interrogator antenna. Aircraft close to the interrogator could receive, decode and respond to interrogations even when they were in the back lobes of the antenna. This often caused a “ring-around” trace on the display so that the controller really had no idea where the targets were. This was particularly serious for interrogators located at airports where the traffic density is high and where it is very important for the controller to have accurate and reliable surveillance. The first patch was to put a “High Sensitivity” and “Low Sensitivity” position on the transponder control panel. When flying near an interrogator or at controller request, the pilot would select “Low Sensitivity.” This procedure was not particularly effective and the Slide Lobe Suppression technique was instituted. All modern 4096 transponders have this feature. The interrogator broadcasts P_2 on the omni-directional antenna 2 usec after P_1 . If the transponder receives P_2 with a signal strength more than 9db below that of P_1 it is unaffected and goes on to decode P_3 if it is received. If the P_2 pulse is stronger than 9db below P_1 the transponder is suppressed, that is, it will not answer any interrogations for the next 35 usec. The specification actually is that if P_2 is weaker than 9db below P_1 the transponder will decode and reply to 90 percent of the time. There is also a patch on the Slide Lobe Suppression patch called Improved Slide Lobe Suppression.

Over-Interrogation. As more interrogators are installed on the ground, the transponders are asked to respond at a very high duty cycle. At high altitude an aircraft may be in line of sight of over 100 interrogators at one time. The transponder has a feature called “Reply Rate Limiting” which begins to decrease the receiver gain and triggering sensitivity when a given level (presently 1200/sec) of interrogations are received. The theory behind this is that the interrogators nearest the aircraft are providing surveillance data to the controllers interested in that aircraft. The signals from these interrogators will be stronger than those

from distant interrogators and the transponder will answer the nearby interrogators and ignore the distant interrogators.

Fruit and Garble. As might be imagined, the beacon system has some interference problems. Figure 2 shows this diagrammatically. The FAA has names for the different types of interference. "Fruit" is the term for a signal received at one interrogator from an aircraft which is responding to a different interrogator. The Pulse Repetition Frequency (or PRF) of the interrogators runs typically between 300 and 400 interrogations per second. The FAA takes some pains to ensure that interrogators in a given geographical area have PRF's which are different enough so that fruit received at a given interrogator does not occur in consecutive Pulse Repetition Periods at the same time from the start of the range strobe at that interrogator. A device called a "Defruiter" is installed on the video output of the interrogator receiver. This device is essentially a delay line, either analog or digital, which compares the video return during one PRP with the return during the preceding PRP. Only those returns which match for two consecutive PRP's are allowed to escape and proceed to the controller's display. The defruiters appear to solve the problem very well. The author has seen radar scope pictures taken at Los Angeles with the defruiter bypassed and there are so many false targets that the display is useless. It should be clear that if adjacent interrogators had identical PRF's we could have the phenomenon known as "Synchronous Fruit" and this would get through the defruiter. There is another interference phenomenon known as "Garble" or "Synchronous Garble." This occurs when two aircraft replying to an interrogation are within approximately $1 \frac{5}{6}$ miles of the same range from the interrogator. The replies as received at the interrogator come back overlapped and it is clear that no defruiter type of device can do much about it. There have been attempts to "deinterleave" these garbled replies but they have had marginal success at best. This synchronous garble is a fundamental problem because the ATCRBS loses reliable surveillance information when aircraft fly near one another which, of course, is just when we need reliable surveillance information the most.

Antenna Problems. The present FAA ATCRBS interrogator antenna is 28 feet long and only about $1 \frac{1}{2}$ feet high and is mounted on top of our primary radar antennas. The vertical pattern is very wide and we have serious problems with antenna lobing and multipath effects. We have measured 50db nulls in the pattern when looking out over calm water and 20db nulls due destructive cancellation by reflections off terrain are fairly common. We can minimize these effects by careful selection of sites and we have an aggressive program to develop and procure antennas with much larger vertical aperture which should really solve this problem as well as some others. There are several other problems with the present beacon system and patches which have been applied or are being developed.

The purpose of this paper is not to describe in exquisite detail all of the defects of the present system but rather to indicate how we propose to eliminate these defects and at the same time to add new features and capabilities to the system. The system in existence today works mainly for one reason--the human controller watching the display is aware of the defects and has learned to live with them because it's the only system he's got. If a target goes into a fade because of antenna problems he knows from experience that it will come out in a few seconds. If two targets merge he doesn't get nervous because he knows they have safe altitude separation. Further, he doesn't swap tracks because he knows who they are and where they are going.

One of the major goals of our present effort in air traffic control is to apply automation to reduce the controller workload and to enhance safety. A computer performing radar tracking is not nearly so tolerant of the foibles of the present surveillance system as is the human controller. Noisy or missing data tend to make the computer very nervous whereas the controller expects it. Additionally, if the computer is really to help the controller in his job it should be able to communicate with the aircraft automatically. Our ultimate goal is the full automation of air traffic control with the human controller in a supervisory and troubleshooting role. The improved surveillance system or, for this journal, telemetry system we are developing to eliminate the problems described, and also to provide automatic digital communication with the same equipment, is called the Discrete Address Beacon System or DABS for short. It is probably clear by now that the FAA has the distressing habit of using more acronyms than even the Department of Defense or NASA but one gets used to it after a while. The DABS concept is not really new, it was recommended to the FAA by the Air Traffic Control Advisory Committee in 1969 and if one looks at the report of Special Committee 31 of the Radio Technical Commission for Aeronautics of 1948 we see that the system recommended in that report is strikingly similar to the DABS.

The basic concept of the DABS is straightforward. Each aircraft is assigned a unique digital code or address and responds only when called by name as opposed to the ATCRBS practice of responding to all valid interrogations. This technique eliminates the basic root cause of the problems of over-interrogation, fruit and garble; the addition to this of an improved interrogator antenna with sufficient vertical aperture to greatly reduce multipath effects should provide a very reliable surveillance system. In addition, since each aircraft must decode and identify its own address, it is now technically and economically reasonable to include some data bits in the discretely addressed interrogation. The message will be decoded and displayed only in that aircraft being discretely addressed. The number of interrogations per aircraft per antenna scan will be decreased from the present 20 to 40 with ATCRBS to one or two with the DABS. This implies the necessity for monopulse techniques on the ground for estimating the azimuthal position or bearing instead of the presently used center-marking technique. The monopulse technique is more complex but

we expect to double our present azimuth estimation accuracy in addition to eliminating fruit and garble. The scan rate of our interrogators is approximately one scan per four seconds for terminal or airport radars and one scan per ten seconds for enroute radars. The DABS is expected to solve most of the known problems with the beacon system and to provide a very high capacity, accurate surveillance system with integral data link at a very modest cost.

As noted above, the basic concept of the DABS is straightforward; the computer has in file the position and address of all aircraft in the assigned surveillance area of the associated interrogator. As the antenna rotates the computer orders the roll call so as to catch each target in the beam and also so as to interrogate targets during a PRP whose ranges are such that synchronous garble will be avoided. There is also a "general call" sent out frequently to elicit responses from those aircraft which are not yet being discretely addressed and to enter them automatically into the track file without adding to the controller's workload. Also, hand-offs from interrogator to interrogator will be performed automatically without adding to controller workload. There will be provisions for interrogator sites adjoining a site which fails to automatically pick up the load of the failed site insofar as line-of-sight limitations will permit.

The DABS system described so far should sound credible and manageable. It is a big job but clearly feasible. In fact one can almost hear some of the older heads saying "Why, shucks!--that's nothing but Time Division Multiplex. We had an IRIG Standard for that in the Spring of nineteen and ought-seven---or was it ought-eight?"

Before the reader jumps to the conclusion that we have taken on too simple a job let us examine some of the other minor constraints that come with it. As noted above, the ATCRBS system is widely implemented in both civil and military aviation in this country. In addition it is widely, almost universally, accepted internationally and is protected by formal treaties with most foreign countries. This means that our ground-based system will have to service ATCRBS for many years in the future. In addition, both the FAA and the aviation community at large have historically been very slow to implement new electronic systems, particularly so for the aviation community if they do not perceive a benefit to be gained by the purchase and installation of new equipment. The FAA is slow, mostly because of the chronic shortage of money for new equipment. We are also charged with the safety of aviation, particularly commercial aviation. This means we can't turn off the world and stop giving service while we and the aviation community install a new system. All these constraints simply mean that the new DABS system must be completely compatible with the old ATCRBS system. We will probably install DABS interrogators slowly, beginning at large terminals such as New York, Chicago and Los Angeles. We can't expect an aircraft operator to buy and install a new DABS transponder unless it will also perform the ATCRBS function when he flies to areas where the ground-system has

not yet been converted to DABS. Similarly, the new DABS ground stations must also be compatible with old ATCRBS transponders which will no doubt be protected by a “grandfather clause” as well as treaties with other nations. The U. S. aircraft fleet is, roughly speaking, comprised of 3,000 commercial air carrier aircraft, 20,000 military aircraft and 140,000 general aviation aircraft. The majority of the general-aviation aircraft have a fair market value of perhaps \$10,000. Avionics are expensive and we want to encourage as many owners as possible to purchase and install DABS transponders. This means that the design should be as simple and inexpensive as we can make it consistent with adequate performance. The requirements for compatibility with ATCRBS and for low cost drive one inexorably to the conclusion that the new DABS system should operate at the same frequencies as the ATCRBS system. We have now arrived at the nub of the reason why our particular telemetry project is interesting. After having outlined the gory details of why 1030 MHz and 1090 MHz are the busiest frequencies in the world except possibly for Citizens Band, it now appears that we are going to ask the aviation community and the FAA to spend over \$1 billion to put our fancy new DABS system at these same frequencies. This was not a decision made lightly or in the absence of data.

We have engaged the Lincoln Laboratory of the Massachusetts Institute of Technology to help us with this problem. Lincoln has examined many possibilities and alternatives and concluded that operation at 1030 and 1090 MHz is both feasible and desirable. Lincoln has performed design studies which included careful attention to avionics costs. One of the most obvious ways for DABS to co-exist with ATCRBS is for DABS to use one of the constant envelope phase or frequency modulation techniques. Lincoln looked at Coherent Phase-Shift Keying, Differential Phase Shift Keying, Frequency Shift Keying, Quadriphase and others. Based on avionics cost considerations, Lincoln has concluded that Pulse Amplitude Modulation at 1090 MHz for the transponder reply is indicated because coherent power at the 100-500 watt level is expensive. Lincoln has also concluded that the uplink, that is, the 1030 MHz interrogation, can be DPSK without significant cost impact on the transponder. Error detection on both the uplink and the downlink seem reasonable, particularly with the availability of low cost, high reliability digital integrated circuits. Basic precepts of the Lincoln design are that the ground-based facility shall do ATCRBS part time and that the DABS uplink message shall include as a leader the P_1 and P_2 pulses to suppress ATCRBS transponders in the beam and also be of short enough duration to be within the minimum suppression time (25 usec) of the ATCRBS transponders which might receive the signal. A simple and easily derived existence theorem for a single DABS facility of this type is that it could track 2000 aircraft, keep a teletype printer busy full time in each of them and still have a reserve capacity of a factor of four. Now that's telemetry.

One of our primary goals in the DABS program is that the purchaser of the first DABS transponder receive services and benefits far in excess of those he would receive had he purchased an ATCRBS transponder. The most immediate service we can offer is an

improved separation service. We are proposing that the ground-based system would, via the DABS data link, apprise the DABS equipped aircraft of all ATCRBS traffic in his area. We would tell him the relative altitude and relative bearing of this traffic and indicate to him whether the range and range-rate of this traffic made it a threat to him.

Even though our ultimate goal is the complete automation of air traffic control we realize that this will not be feasible until a large fraction of the fleet is DABS equipped. If our experience with ATCRBS is any indicator, this could take many years. We believe, however, that the ground-based automatic separation assurance service could be available to the very first DABS purchaser when flying in areas where the surveillance system had been converted to DABS. As we converted more and more ground facilities, he would get more and more service. We visualize three basic kinds of airspace in the future air traffic control system: Positive controlled, mixed and uncontrolled. Aircraft flying in positive controlled airspace will be required to be on a flight plan and under positive control. This airspace would be at high altitudes and around the major terminals, typically the places where commercial turbo-jet aircraft operate. Mixed airspace will be, for example, between 6,000 feet and 12,000 feet and around many controlled airports but not the major terminals. Aircraft flying in this airspace would be required to carry an ATCRBS or a DABS. We will automatically advise all DABS equipped aircraft of nearby traffic and whether this traffic constitutes a threat. If a collision appears imminent we will automatically send collision avoidance maneuver commands to the DABS equipped aircraft. This concept has acquired the name Intermittent Positive Control because we only control aircraft when it is absolutely necessary. Most of the time the pilots fly wherever they choose. The low altitude airspace remote from controlled airports will probably remain uncontrolled with no requirements for carrying a transponder. We will have surveillance coverage over much of this airspace and will inform DABS equipped aircraft of traffic. However, we will not send maneuver commands because of the possibility of vectoring the DABS aircraft into a non-transponder aircraft not seen by the surveillance system. There are other classes of messages we will also send to the aircraft via this DABS link as the automation of the ATC system progresses. The message format also permits sending messages containing air traffic control instructions. These messages would typically relate to assigned altitude, heading and airspeed as well as VHF voice frequency assignment. The format also will permit transmission of clear text alpha-numeric messages for the more sophisticated users who might want information concerning weather, route clearances or any other subject requiring longer clear text messages. The technical characteristics of the proposed system are fairly easily defined. First, both the ground and the airborne components of the new system must perform all the normal functions of the ATCRBS system for the reasons I have described earlier. For the DABS mode Lincoln Laboratory is leaning towards Differential Phase-Shift Keying (DPSK) for the 1030 MHz uplink interrogation. The bit rate will be 2-4 megabits/second and both the uplink and the 1090 MHz downlink will have error-detecting coding to help us to work in the presence of

interference. If the transponder detects an erroneous interrogation, it will not reply and the ground will initiate a re-interrogation. If the ground receives an erroneous reply, it will initiate a re-interrogation. The aircraft response at 1090 MHz will be Pulse Amplitude Modulated because of cost considerations. The bit rate will be approximately 2 megabits/second. The aircraft message will be used chiefly for surveillance purposes and to insure that the aircraft had properly received and decoded any messages sent to it. The aircraft message will also carry the barometric altitude of the aircraft as derived from an encoding altimeter. We are considering 24 bits for the discrete identity code--this provides something over four million unique addresses which should be adequate for the foreseeable future. We will have a "lock-out" feature also. This means that any aircraft being tracked in the DABS mode could be instructed automatically by the ground to not respond to ATCRBS interrogations. Thus, as more aircraft converted to DABS we would begin to unload the ATCRBS system and reduce the interference problems. As mentioned above, the system also contains an "all call" mode which will elicit responses from DABS equipped aircraft which are not being discretely addressed and will then automatically begin to interrogate these aircraft by their unique addresses. It is important that we make this new surveillance system operate automatically without adding to controller workload. Lincoln Laboratory has been testing this system this summer and we are preparing to demonstrate with actual flight test that we can provide a safe, economical and convenient automatic separation assurance service using this form of telemetry.

ATC SYSTEM CONCEPT: NAVIGATION, COMMUNICATION, SURVEILLANCE, CONTROL

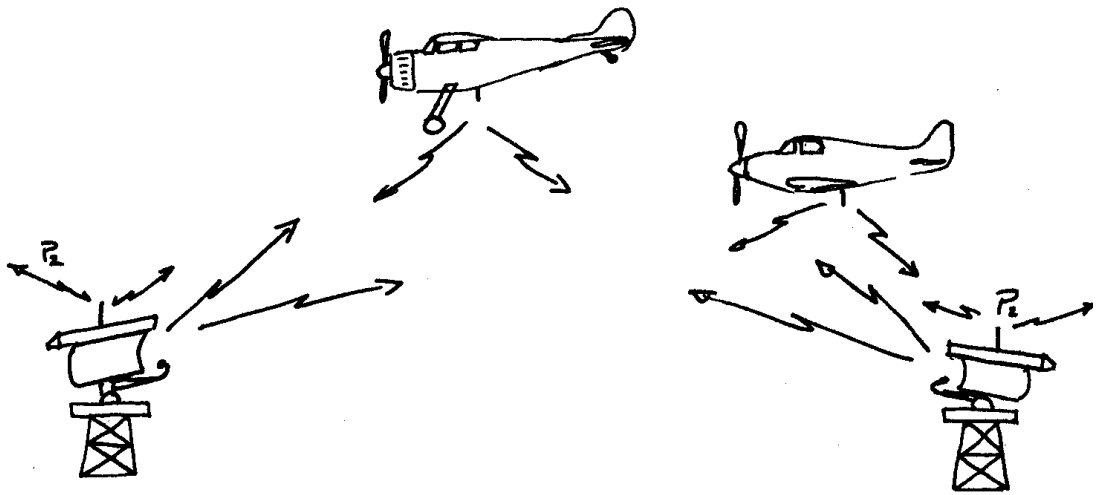
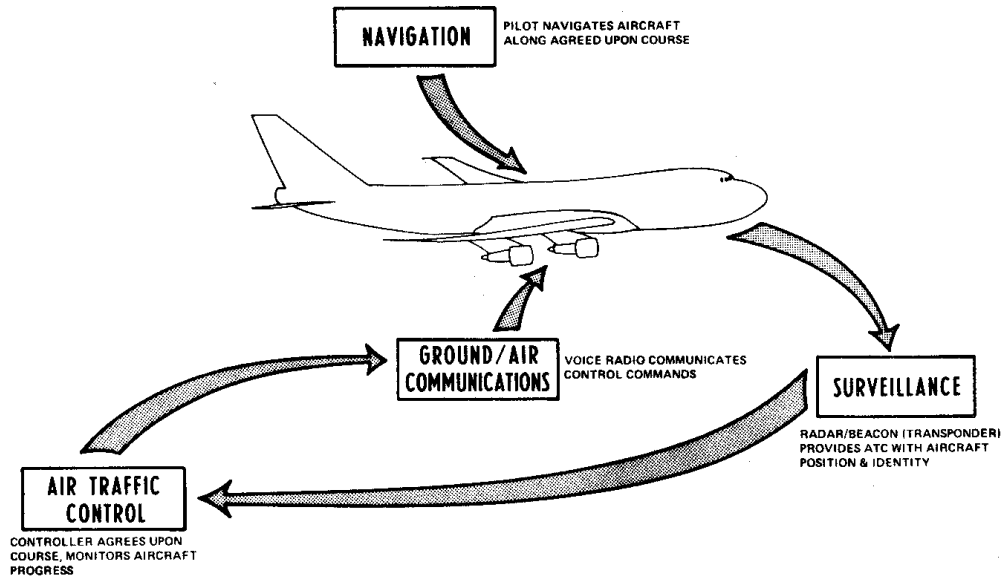
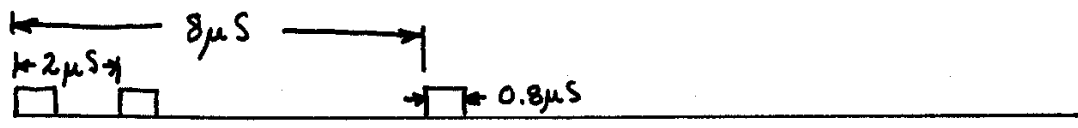
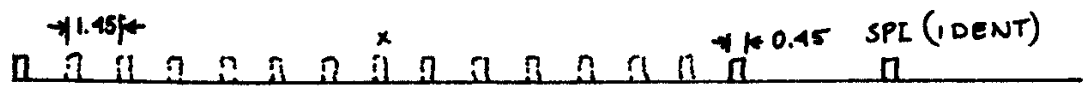


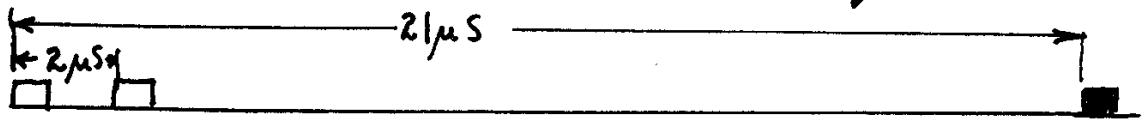
FIGURE 2



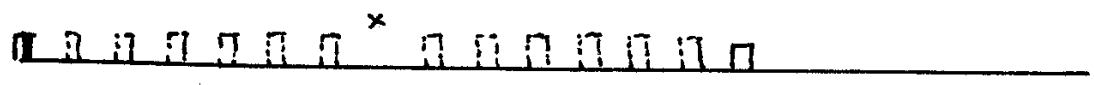
MODE A INTERROGATION - 1030 MHz



MODE A RESPONSE - 1090 MHz



MODE C INTERROGATION - 1030 MHz



MODE C RESPONSE - 1090 MHz

FIGURE 3

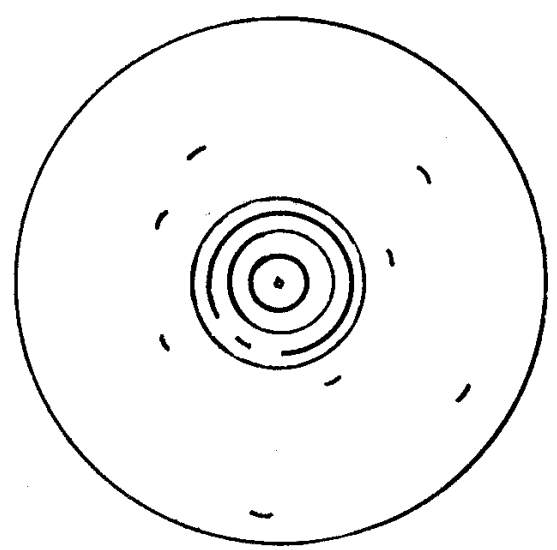


FIGURE 4

SIDELobe RETURNS CAUSE "RING-AROUND"