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Direct Aircraft Velocity Determination By L-Band Moving Target Detector Radar

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Final Report

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16. Abstract

The Moving Target Detector (MTD) radar can be used to measure the phase difference of echoes from aircraft returns. From these measurements one can determine directly the radial component of aircraft velocity. Present practice is to determine velocity indirectly from radar position measurements. Results of measuring phase shift differences and corresponding aircraft velocities using an L-Band MTD radar are presented. Observations were made in a clutter free envioronment.

The standard deviation of phase shift differences made from observations on a B727 airplane at a distance of 100 nmi was generally found to be 5 degrees, corresponding to a standard deviation of velocity component of 1.2 knots.

The standard deviation of phase shift observed from six slower moving airplanes indicates the standard deviation of phase is generally 18 degrees or less, cor responding to a standard deviation of velocity component of 4.3 knots or less.

Reliability is generally 94% for the B727 airplane and about 90% for the small airplanes, although poorer reliability is observed with tangential flight paths.

Direct measurement of velocity can be used to provide increased precision in predicting aircraft motion over the short term (2 minutes). Recommendations that a velocity measuring radar based on the MTD be developed and deployed are included in this report.

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METRIC CONVERSION FACTORS

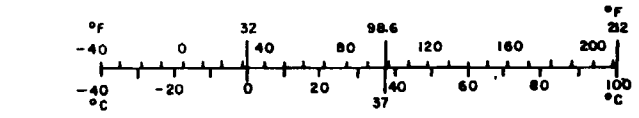
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by*	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

1.1 Example of Requirement for Aircraft Velocity Data

In the National Airspace System (NAS) aircraft velocity is measured and aircraft motion is predicted by making use of position reports provided by the various radars. Any velocity calculated from these reports is necessarily subject to a time lag because the position data is received rather slowly. If velocity can be measured directly, and it may be possible to do so by utilizing the phase measuring capability of the Moving Target Detector radar (MTD), then this time lag can be eliminated.

The fundamental motive for attempting to measure velocity directly is to enhance safety in the System. A principal "consumer" of aircraft velocity data is the Conflict Alert system (CA) which acts as one of the final lines of defense against midair collisions in the en route portion of the System.

The Conflict Alert system operates by predicting aircraft motion over the short term, providing alerts to the controller whenever the velocity vectors of an aircraft pair indicate that the separation between the two members of the pair will be less than a minimum safe distance within a short period of time. Typically it is desired that an alert be issued if it appears that two aircraft will be separated by a distance of less than 4.8 nmi (8.9 km) during the ensuing 2 minutes.

The Conflict Alert system has been in operation as part of the National Airspace System since 1976 and during this six year period it has given satisfactory performance. Nevertheless it is possible to construct examples where a hazardous air traffic situation can develop and the desired 2 minute warning time is not provided. Figures 1-1 through 1-3 illustrate one of these. When the CA system can alert the controller to the close approach in the example there is less than 36 seconds of time available to resolve the situation. Reviewing what must be accomplished within this time so that evasive action can be taken, it appears that a warning time of 36 seconds is inadequate.

The likelihood of the occurrence of a situation like that presented in the Figures can be expected to be very low. Over the course of years, however, the occurrence of even very unlikely events must be expected and, if these events are hazardous, there must be provision for dealing with them. The example presented in this subsection does not seem to fall into the category of the incredible. It follows that if it is feasible to provide additional warning time in similar cases, then such additional time should be provided.

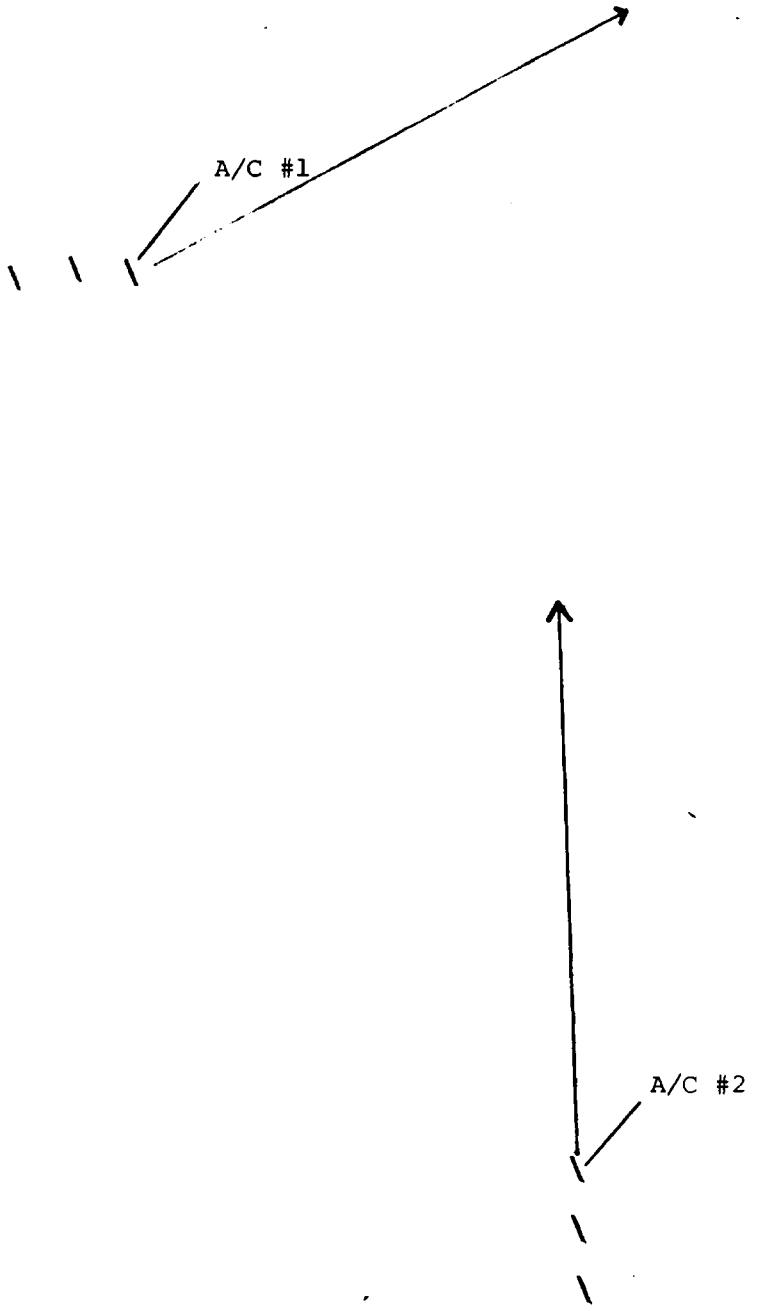


Figure 1-1. In this scenario two aircraft are at speeds of 450 knots. A/C #1 is in a shallow turn to the right and A/C #2 is moving directly north. The controller has requested that 2 minute velocity vectors be displayed and as a result he/she is presented with this picture of the air situation. No hazard is indicated.

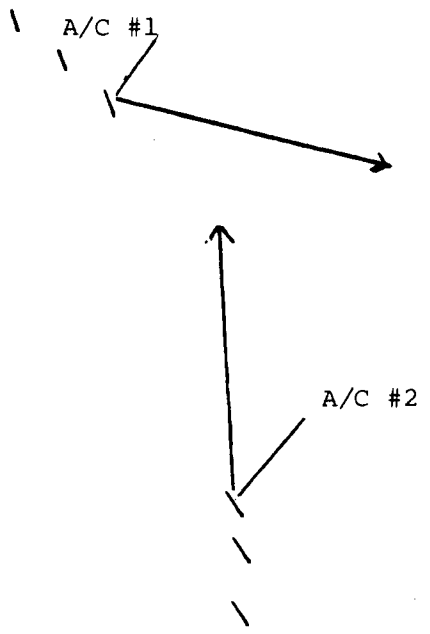


Figure 1-2. The situation illustrated in Figure 1-1 has developed in 72 seconds to the situation shown here. 1 minute velocity vectors are displayed. The Conflict Alert subsystem has not tripped. An alert controller may have become aware that the situation is hazardous by monitoring the aircraft position reports. Note that the velocity vectors indicate a safe air situation as A/C #1 is expected to pass in front of A/C #2.

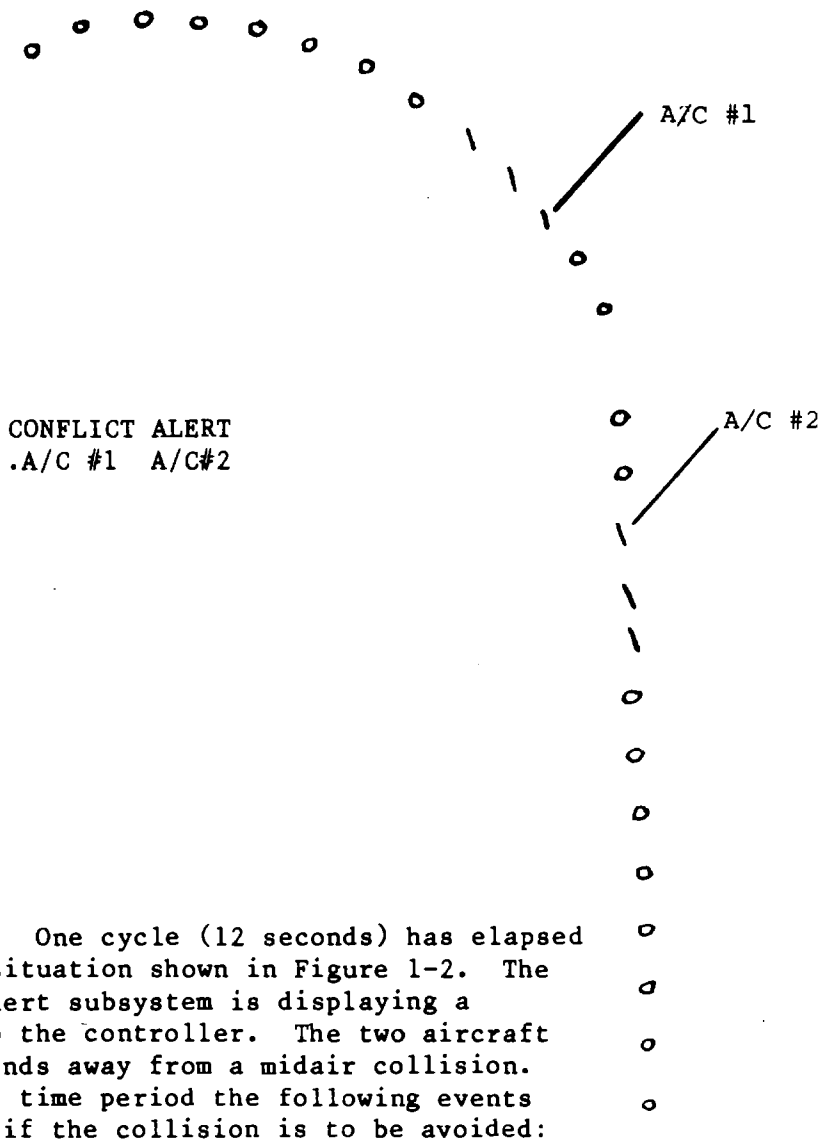


Figure 1-3. One cycle (12 seconds) has elapsed since the situation shown in Figure 1-2. The Conflict Alert subsystem is displaying a Conflict to the controller. The two aircraft are 36 seconds away from a midair collision. Within that time period the following events must occur if the collision is to be avoided: (1) the controller must evaluate the situation, (2) he/she must communicate appropriate instructions to one of the pilots, (3) the pilot must act and (4) the aircraft must respond.

The total history of the location of the two aircraft in the scenario, past and perhaps future, is shown by open circles. The controller is aware of the position reports (shown as \'s) and of the Conflict Alert warning with the aircraft identification attached.

The reason for the short warning time in the example can be traced to the lag of the calculated velocity vector associated with the aircraft which has drifted into a turn. Such lag will always be found when predictions of aircraft motion are based on radar position reports. The reports come in somewhat slowly, at 10 or 12 second intervals in the en route system, and they are processed in such manner that aircraft maneuvers are recognized only after any change in motion is well under way. In Figure 1-1, for example, the direction of the calculated velocity vector of the aircraft in the shallow turn lags 33 degrees behind the actual velocity vector of that aircraft (See Appendix, page 37). It is this lag which is reponsible for the comparitively late call of "Conflict Alert".

The lag in estimating velocity vectors can be reduced or perhaps eliminated entirely if the NAS ground equipment can be provided with aircraft velocity information directly, rather than being required to calculate it from position reports. It is the purpose of this report to examine the possibility of making a direct determination of aircraft velocity by using the phase information contained in the radar echo of the aircraft.

By making proper use of such information one can essentially solve the problem of the measurement of aircraft velocity. While it is true that only one of the three components of velocity is directly measured, for the case of civil aircraft the determination of only one component is sufficient to make a complete determination of velocity. This is so because, for these aircraft, speed (absolute value of velocity) necessarily changes slowly and can be assumed known from previous position measurements. The case of military aircraft which are capable of significant longitudinal acceleration and deceleration (by the use of increased thrust or by speed brakes) has not been investigated.

The observations which form the basis of this report were made for the purpose of supporting a feasibility study on the detection of aircraft maneuvers using phase data. Although not exhaustive, they support the conclusion that it is indeed possible to determine accurately the velocity of civil aircraft using phase shift data.

1.2 Outline of This Report

In Section 2 following is an analysis of pulse to pulse phase shifts of the radar echo. From these phase shifts, using a two step procedure, one may estimate aircraft velocity. First one makes a coarse estimate of velocity from a pair of position determinations. The second step involves making use of phase shift data to refine the coarse estimate.

The analysis is essentially based on the processing of the Moving Target Detector (MTD) radar. Several examples of the results expected of MTD processing are included in Section 2.

In Section 3 are described observations which were conducted to verify the ideas introduced in Section 2. The principal results of Section 3 are the estimates of the various probabilities of acquiring phase shift data with the MTD and of the precision associated with the data so acquired.

Another result appears to contradict widely held views. Commentators have long suspected that phase shift measurement on aircraft echoes would be corrupted by modulations from propeller or compressor motion (References 1 through 3). This corruption was not observed in the data reported in Section 3.

The results of Section 3 are based entirely on observations made during a single two hour observation period. Operationally, one may expect results somewhat superior to those reported. There are two reasons for this optimism: (1) the numerical analysis can be improved, (2) the adjustment of the equipment on the occasion of its use seems to have been suboptimal. Equipment specifically designed to measure phase shift, (the MTD is not so designed) can be expected to provide results superior to those reported. See subsection 2.6 on page 16.

It seems reasonable to conclude that, even though the amount of data is limited, the quantities reported in Section 3 fairly represent data which can be made available to the air traffic control system in the future.

Conclusions and recommendations form Section 4 of this Report. It is recommended that effort be continued with the goal of deploying a velocity measuring radar in the en route portion of the National Airspace System towards the end of the decade. The radar must be supported by appropriate processing software. The ultimate purpose is to increase safety in the aviation system, by preventing the occurrence of situations like those described in Figures 1-1 through 1-3.

2. PHASE SHIFT MEASUREMENTS, THEORY

This section presents an overview of the origin of the phase shift associated with radar returns from aircraft. It will be shown that phase shift arises from aircraft motion and hence is directly proportional to a component of velocity. It follows that a measurement of phase shift is essentially equivalent to a measurement of velocity component.

Processing of radar echoes by the Moving Target Detector (MTD) radar is examined. Developed primarily for the purpose of detecting aircraft radar echoes in the presence of echoes from terrain and precipitation, the MTD computes the phase of these echoes as part of its detection function. The results of such computation can be used to determine aircraft velocity.

This section concludes with remarks concering a hypothetical device which would be dedicated to measuring the phase of radar echoes from aircraft. Improvements over MTD results seem possible, but at present these improvements are also hypothetical.

2.1 Origin of Phase Shift Data

In the National Airspace System the presence of aircraft is determined by generating and propagating a series of short, powerful bursts of electromagnetic energy and listening for echoes of these bursts in a suitably tuned receiver. For the long range radars, those with a capability of reaching 160 nmi, the bursts are normally 2 usec in duration and consist of about 2600 cycles of electrical energy. A typical long range radar carrier frequency is thus 1300 cycles per microsecond or 1300 MHz.

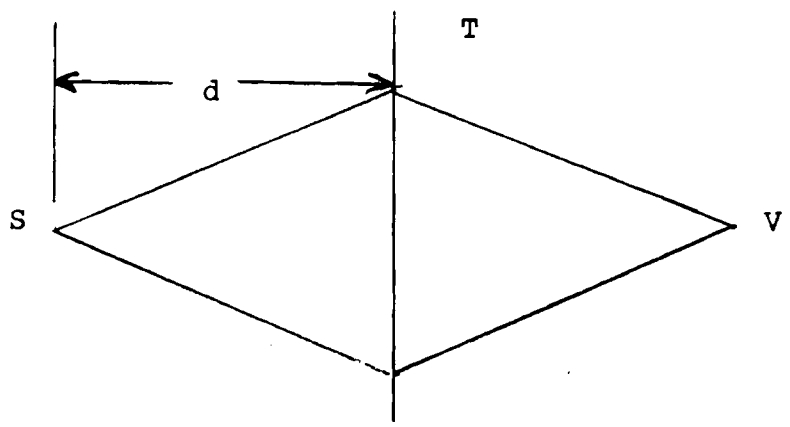
The phase of the radar echo from any target is simply the time which has elapsed between the start of propagation of the radar pulse and its reception in the receiver. A suitable conversion of scale is required. For the 1300 MHz carrier in the example the appropriate conversion is 360 degrees for each 769 picoseconds (769×10^{-12} seconds) of time delay.

The phase of an isolated pulse is usually very large and absolute phase is not measured. The phase difference between pulses in a series of pulses uniformly spaced in time can be measured with an accuracy of a few degrees. This is because with the phase measuring techniques available only the principal value of the phase is measured. If the phase of a return is written as 360 degrees times $(n + q)$ where n is an integer and q is a positive proper fraction $(0 \leq q < 1)$, then only the fraction q is measured. Such a quantitiy is of course useless for range measurement. Differences in q, however, are useful in velocity measurements. In fact the basic equation which relates phase shift differences to aircraft velocity is:

$$\text{Phase Shift} = 720 \text{ degrees} \cdot (\dot{r}/c) \cdot (f/prf) \qquad (2\text{-}1)$$

where $\dot{r}$ is the component of velocity along the line of sight from the radar, f is the radar carrier frequency and prf is the symbol for pulse repetition frequency (prf = 1/(time since last pulse)). The symbol c represents the velocity of the electromagnetic disturbance, a universal constant equal to 583,000,000 knots.

To fix ideas firmly in mind it is instructive to follow in detail a derivation of equation 2-1. The following sketch represents the radar transmitter/receiver S, an aircraft, represented by its conducting skin, T, and a virtual source, V. The radar echo is viewed as arriving at receiver S, having been generated by virtual source V. Measuring time from the instant that the radar signal begins to be transmitted, the time of arrival of the echo at S is $2 \cdot d/c$, where d is the sensor to aircraft distance at the time the radar pulse reaches the aircraft.



The phase of the return signal can be defined as being equal to 360 degrees times the quantity $2 \cdot d \cdot f/c$. When a second pulse is transmitted, at a time later by the quantity 1/prf, the same considerations apply as in the sketch except that distance d is replaced by $d + (\dot{r}/prf)$. The phase of the echo from the second pulse is equal to 360 degrees times $2 \cdot (d+(\dot{r}/prf)) \cdot f/c$. By taking the difference of the two phases one arrives at equation 2-1.

Although aircraft are clearly not, as suggested in the sketch, infinite conducting planes, they can be considered such for present purposes provided the aspect of the aircraft does not change significantly over the time in which it is being observed, the time on target. For the en route MTD the time on target is 0.02 seconds. This is sufficient time for a propeller to sweep through almost one revolution, or for a turbine compressor blade to go through several revolutions.

It may be argued that propeller and turbine motion can indeed affect aircraft aspect. However, one might note that a propeller has a radar cross section which is far smaller than that of the wings, fuselage and tail surface of an airplane and hence its influence on phase should be comparatively small. One might expect turbine compressor blades to have even less effect on aircraft aspect and therefore on phase. Thus for airplanes, equation 2-1 is expected to hold strictly. As will be shown in section 3, this expectation appears to have been fulfilled.

If the frequency of the return pulse is known then it is possible to measure the phase of the return signal by various techniques. These consist of making a comparison of the phase of the echo signal with the phase of a local oscillator tuned to the echo frequency. Of course only the principal value of the phase is measured, i. e. the phase modulo 360 degrees.

For these techniques to work the two frequencies involved, that of the local oscillator and that of the echo, must be closely matched. If pulse duration is dt then the allowed difference in frequencies, df, must be such that the quantity $df \cdot dt \ll 1$. Any mismatch in frequencies will make the estimate of phase difference less precise. When the quantity $df \cdot dt$ approaches unity the phase difference of the two signals cannot be measured by the techniques being considered. Indeed the concept of phase difference loses its meaning in this case.

A source of frequency mismatch which is uncorrected in the MTD arises from the motion of the target aircraft. As each successive wavefront interacts with the aircraft it does so at a time later than its prodecessor by the quantity 1/f. During this period the sensor to aircraft distance changes by the quantity $\dot{r}/f$. If d is the sensor to aircraft distance at the time of the beginning of interaction between pulse and target then the wavefronts of the echo are received at the receiver at times equal to

$$\frac{2 \cdot d}{c}, \quad \frac{2 \cdot (d+\dot{r}/f)}{c} + \frac{1}{f}, \quad \frac{2 \cdot (d+2\dot{r}/f)}{c} + \frac{2}{f}$$

The reciprocal of the difference in arrival times between successive wavefronts is the echo frequency. This frequency is readily seen to be equal to $f/(1+2 \cdot \dot{r}/c))$. The frequency is said to be shifted by a fraction $2 \cdot \dot{r}/c$ (Doppler).

For present purposes the Doppler shift is of no importance. The frequency f is about 1300 MHz and the pulse width is always less than 6 microseconds. Even for an aircraft moving at a radial speed of 1000 knots the Doppler shift multiplied by the value of the pulse duration, $(df \cdot dt)$, is less than 0.03. Any effect of this small quantity does not modify the ideas introduced in this subsection. It follows that phase differences can be measured using a local oscillator as the frequency source.

The situation is different for the case of the secondary radar system. The frequency of the radar echo, in this case a beacon response, is allowed to be off its nominal frequency of 1090 MHz by $\pm$ 3 MHz (DOT/FAA Order 1010.51A, 1971). Since the pulse duration in this case is 0.45 microseconds, the product df.dt equals 1.4. Hence conventional phase measuring techniques will not function with the secondary radar system. To them there must be appended some scheme of determining the reply frequency to within an accurancy of about one part in 10,000.

2.2 Example of Phase Shift.

A phase shift is conveniently pictured as the rotation of a vector in phase space. For definiteness consider the following situation. It is typical of those found in the en route part of the National Airspace System: (1) the carrier frequency is 1300 MHz, (2) the pulse repetition frequency (prf) is 400 Hz, (3) the component of aircraft speed along the line of sight is 200 knots. Inserting these quantities into equation 2-1 shows that the pulse to pulse phase shift is expected to be 803 degrees or, taking the principal value, 83 degrees ($803° - (2 \cdot 360°) = 83°$).

It is feasible to measure the principal value of the phase differance between returns. The accuracy with which this measurement can be made will be the subject of section 3. To anticipate somewhat, the standard deviation of the measurement of the principal value of phase shift from returns from a B727 aircraft is expected to be about 5 degrees.

Suppose a pair of successive aircraft position reports are input to a processor of position reports, or "tracker", as follows:

Report 1, range 72 nmi, phase shift not relevant
Report 2, range 72-5/8 nmi, phase shift 83 degrees.

These reports are assumed to be received 12 seconds apart, corresponding to the rotation period of the radar antenna. With the technology deployed at the present time the position data but not the phase shift data are available. Phase shift data can be made available when the next generation of long range radars is deployed, about 1990.

At the time the second report is received the tracker can estimate the radial velocity of the aircraft as 188 knots ((72-5/8 nmi - 72 nmi)/12 seconds). The distance datum is reported to a precision of 1/8 nmi so that the radial velocity calculated is inexact and at best one is able to estimate that the range rate of the aircraft is greater than 150 knots and less than 222 knots.

If the phase shift datum, with a principle value 83 degrees, is available then the accuracy of observed range rate can be considerably improved. By manipulating equation 2-1 it is found that a range rate of 21 knots corresponds to an 83 degree phase shift. Other possible values of range rate consistent with the 83 degree principle value of phase shift are: 110 knots (543° phase shift), 200 knots (803° phase shift) 290 knots (1163° phase shift). From the scan to scan data the clear choice is 200 knots (803° phase shift).

The accuracy of this estimate, expressed as one standard deviation, is 1.3 knots if the aircraft is a large one like the B727 (Section 3 following). Accuracies of this order are believed to be of value in providing early estimates of potentially hazardous air situations. (Subsection 1.1, also Reference 6.)

2.3 Determining Phase Shift

A straightforward method of determining any uniform rate is to subtract the earliest measurement of the quantity to be measured, in this case phase, from the latest determination of that quantity. The difference is divided by the time difference of the two measurements to arrive at the rate.

The method of determining of the value of pulse to pulse phase shift in the National Airspace System has not developed along these lines. Instead a rather indirect approach, associated with the development of the MTD radar, is used. This is a phase processing system using suboptimal processing for phase shift determination. For a brief discussion of so-called "optimal" determination of phase shift see subsection 2.6 (page 16).

The original intent of the MTD was not to measure phase shift as such but rather to reliably detect the presence of aircraft in weather clutter or in ground clutter. Incidental to this detection the MTD calculates pulse to pulse phase shift. During early development only limited design freedom was allowed because processing speeds were limited. An ingenious design was developed which divided phase space into eight domains.

The MTD design evolved from this concept. As prepared for procurement the design divides phase space into eight domains, usually called filters. The filters are centered at pulse to pulse phase shifts as shown on the following page:

Filter	Phase Shift (pulse to pulse)
0	0
1	84°
2	96
3	135
4	180
5	225
6	264
7	276

Filter zero covers the largest volume of phase space. The size of filters 1 and 7 are squeezed to accomodate the fairly large volume of filter zero. Each of the remaining filters, 2 through 6, covers about 45° of the total phase space of 360°.

The reason for this curious division of phase space arises from the phenomena of clutter, the unwanted radar returns from terrain and precipitation. Filter zero is sometimes called the zero velocity filter (ZVF) and it is expected to include all of the terrain clutter. Weather clutter, if present, is expected to be contained in all eight filters.

Target thresholding in the ZVF is different from that in the other seven filters. A target is declared in the ZVF if the radar echoes stand out from the adjacent background in time. The previous history (eight scans or about 96 seconds) of a physical point in space may show a target (fixed target). If the current echo shows an increase in signal strength above this history then a moving target is declared. Fixed targets are suppressed in the MTD.

In the other seven filters a target must stand out in space from its neighbors in order to be declared present. These filters are associated with weather clutter.

The following quotation is from an early report on the MTD. "These two concepts of thresholding were chosen because of the character of ground and weather clutter. Weather clutter will generally be dispersed in range over several cells, whereas ground clutter is quite independent from cell to cell. On the other hand, weather clutter is quite time varying, but ground clutter in a given cell remains relatively constant in level over long periods of time" (Reference 7).

Since, as will be shown in the Section 3, the sensitivity in the ZVF may be poor, it is desirable that the presence of an aircraft be declared in a filter other than filter zero whenever possible. Note that when a range rate is at or near one of the blind speeds that the pulse to pulse phase shift will result in a response in filter zero. The blind speeds are integral multiples (both positive and negative) of the value of r which makes the expression 2-1 equal to 360 degrees.

In the example on page 10 the first blind speed is 90 knots. Aircraft with range rates of 90 knots, 180 knots (2·90), 270 knots (3·90), etc. will result in replies with zero phase shift. The same is true of aircraft with range rates of -90 knots (90 knots toward the radar sensor), -180 knots, etc.

In the MTD the problem of blind speeds for aircraft which are not moving tangentially (for which $\dot{r} \neq 0$) is treated in the following way. The pulse repetition frequency (prf) is shifted in value every eight pulses by 20%. There results a corresponding shift of the blind speed. As a consequence the return from an aircraft with a non zero range rate will fall in a filter other than filter zero for at least one of the two values of prf.

If the aircraft is moving tangentially there is no alternative but to work with the responses in the zero velocity filter. These responses compete with clutter and comparitively poor detection is to be expected. The nomenclature Moving Target Detector appears to be accurate (but see remarks on the bottom of page 33).

2.4 Three Examples

The Moving Target Detector (MTD) processes the radar responses from targets in groups of eight. If one response of the group is missing no particular harm is experienced, the estimate of phase shift is perhaps less accurate than would be the case if all responses in the group were present.

In filters one through seven interference is declared if one of the replies is approximately 10 dB stronger than the average of the other seven. Target declaration is suppressed in the presence of such interference.

In filter zero the response must exceed the average response for the previous eight scans, usually occurring over a time period of 96 seconds, at a given geographical point in order for a target to be declared at the point.

The MTD processes each group of eight (or fewer) responses eight times. Each process corresponds to one of the eight domains or filters into which phase space is divided. Responses in several adjacent filters are expected from a moving target.

The treatment of the eight responses in each of the eight filters is described in Table 2-1. Note that the process is linear. Note also that the eight responses are not given equal weight in the processing. In general responses 2, 3, 4 and 5 are given greater weight than responses 1 and 6 and that the responses indexed 0 and 7 are weighted least of all.

Three examples of the use of Table 2-1 follow.

TABLE 2-1
Response Coefficients of the MTD Filters

Response of the MTD to a group of eight replies is calculated by multiplying the amplitude of each reply by the coefficient in the Table and taking the amplitude of the resulting sum. This amplitude is normalized by multiplying the sum by the factor shown for each filter.

Filter 0 norm: 1.000	Filter 1 norm: 0.439	Filter 2 norm: 0.315	Filter 3 norm: 0.667
-3	3-3j	-2-3j	-1
-1	-7-4j	-6+9j	3+3j
7	-7+12j	20+7j	-9j
15	13+10j	3-28j	-9+9j
15	10-14j	-28+3j	13
7	-10-9j	7+20j	-7-7j
-1	-6+6j	9-6j	+5j
-3	4+2j	-3-2j	1-j

Filter 4 norm: 0.714	Filter 5 norm: 0.667	Filter 6 norm: 0.315	Filter 7 norm: 0.439
-1	-1	-2+3j	3+3j
4	3-3j	-6-9j	-7+4j
-9	9j	20-7j	-7-12j
13	-9-9j	3+28j	13-10j
-13	13	-28-3j	10+14j
9	-7+7j	7-20j	-10+9j
-4	-5j	9+6j	-6-6j
1	1+j	-3+2j	4-2j

Example 1. Stationary Target.

In filter zero the response is equal to 36. Response in the other filters is zero. This can be seen by inspection of the Table.

Example 2. Optimum speed target

The pulse to pulse phase shift of an optimum speed target is a maximum in filter 4 with a normalized value of 38.6. The response in filter zero vanishes. The response in the other six filters varies. In the following table are listed the normalized response of the optimum speed target in each filter together with the relative power of that response. Power is proportional to the square of the response and, for a target which responds in more than one range cell, is additive over range cells.

Filter	Response	Relative Power	Filter	Response	Relative Power
0	0	0	4	38.6	1.00
1	0.88	0.00	5	16.87	0.19
2	0.89	0.00	6	0.89	0.00
3	16.87	0.19	7	0.88	0.00

Example 3. Target with pulse to pulse phase shift of 83 degrees.

It is an elementary but tedious exercise in complex arithmetic to demonstrate that the normalized responses and power ratios for a target with a pulse to pulse phase shift of 83 degrees are as follows:

Filter	Response	Relative Power	Filter	Response	Relative Power
0	17.95	0.31	4	6.27	0.04
1	32.31	1.00	5	0.02	0.00
2	22.98	0.51	6	2.41	0.01
3	12.5	0.15	7	4.27	0.02

2.5 The General Case

As the three examples of subsection 2.4 suggest, the response of a target in the MTD depends on the pulse to pulse phase shift associated with the target. The response is characterized by a strong return in one of the eight filters, a lesser return in a neighboring filter and lesser returns still or no returns at all in the other six filters. The MTD processes the replies so that the target strength, proportional to amplitude of response, is available in each of the eight filters when this strength is above threshold.

For the weakest targets the response may be in one filter only. In this case the quantities at the top of page 12 may be used to translate a filter number into a phase shift value. The precision of such a resonse is necessarily low and the low precision responses are

expected to be of little value operationally.

In the more usual case one may determine phase shift in the MTD by studying the pattern of the target return in the eight filters. The strongest power reply is associated with the principle filter. The replies in the neighboring filters are compared with this and the phase shift is determined from the power ratios. These are the high precision responses which are believed to be of operational value in the National Airspace System.

Table 2-2 was prepared for the purpose of determining phase shift from the power responses of targets in the eight filters of the MTD. It was constructed by graphical methods from response curves reported as Figures 3.4.5-4B and 3.4.5-5 of Reference 5. It is believed to contain errors which could be avoided if it were reconstructed using digital methods.

These errors probably contribute to the variance observed in the phase shift measurements (Section 3). The amount of such contribution cannot be determined without additional study.

2.6 Alternate Methods of Determining Phase Shift

The primary objective of MTD development was to provide a system which will reliably detect and identify radar echoes from aircraft, particularly when these echoes are found coupled with those from the terrain or from precipitation (clutter). Phase measurement is incidental to this purpose and is in a sense entirely fortuitous. It is reasonable therefore to inquire about what results might be expected of a system designed from the start with the primary objective of measuring the phase of the radar echo.

Two distinct answers are received from such an inquiry depending on whether the MTD is merely modified or whether it is replaced altogether. Only modest improvements in phase shift measurement can be expected from a modification. If an alternate phase measuring scheme is developed, however, an initial analysis suggests very accurate phase measurements may be attainable, at least for strong echoes.

Take first the possibility of modifying the MTD. Note that the MTD as prepared for procurement is designed to determine the value of the pulse to pulse phase shift, α, which maximizes the following sum of eight terms (Reference 8):

$$R_0 + R_1 \cos(\alpha_1-\alpha) + R_2 \cos(\alpha_2-2\alpha) + \ldots + R_7 \cos(\alpha_7-7\alpha) \quad (2\text{-}2)$$

where the R's represent the amplitude of eight successive radar echoes and the angles $\alpha_1, \alpha_2, \ldots, \alpha_7$ represent their phases. Following the usual rules of differential calculus, it may be seen that making use of the MTD approach is equivalent to making the following estimate for pulse to pulse phase shift:

TABLE 2-2

Pulse to Pulse Phase Shift
as a Function of Power Response in Eight Filters

Phase Shift	Response Strongest in Filter	Response Next Strongest in Filter	Ratio	Response Next Strongest in Filter	Response Strongest in Filter	Phase Shift
0	0	1	10^{-6}	7	0	0
6°	0	1	10^{-5}	7	0	355°
11	0	1	10^{-4}	7	0	349
17	0	1	.001	7	0	343
22	0	1	.003	7	0	338
28	0	1	.006	7	0	332
34	0	1	.04	7	0	326
39	0	1	.11	7	0	321
45	0	1	.25	7	0	315
51	0	1	.32	7	0	304
56	0	1	.5	7	0	309
62	1	0	.63	0	7	298
68	1	2	.63	6	7	292
73	1	2	.71	6	7	287
79	1	2	.78	6	7	281
84	1	2	.86	6	7	276
90	1	2	.93	6	7	270
96	1	2	1.00	6	7	264
101	2	1	.707	7	6	259
107	2	1	.562	7	6	253
112	2	3	.63	5	6	248
118	2	3	1.00	5	6	242
124	3	2	.707	6	5	236
129	3	2	.562	6	5	231
135	3	2	.400	6	5	225
141	3	2	.35	6	5	219
146	3	4	.46	4	5	214
152	3	4	.707	4	5	208
158	3	4	.851	4	5	202
163	4	3	.85	5	4	197
169	4	3	.63	5	4	191
174	4	3	.32	5	4	186
180	4	3=5	.20	5=3	4	180

$$\frac{R_1 \cdot \alpha_1 + 2.R_2 \cdot \alpha_2 + \ldots + 7.R_7 \cdot \alpha_7}{R_1 + 2^2.R_2 + \ldots + 7^2.R_7}$$

For uniform returns ($R_0 = R_1 = \ldots = R_7$), the deviation of the estimate of phase shift over the eight filters is thus equivalent to the deviation of an individual estimate multiplied by the quantity 28/140 = 1/5.

If the MTD approach is modified then the estimate of may be made in a way which ordinarily excludes terms indexed as 1 through 6 in expression 2-2. For uniform returns the deviation of the estimate of is reduced from 1/5 to 1/7 of that of the individual estimates of phase. The result is a reduction in deviation, albeit a small one, from the conventional MTD approach.

Continuing along these lines one may manipulate the entries in Table 2-1 (page 14) so that the MTD processor is optimized for phase determination. Note that for the case where the eight responses are uniform, expected to be a very common one, little reduction in deviation is expected. There appears to be no prospect of significantly improving results when estimating phase shifts between the conventional MTD approcach based on Table 2-1 and any "optimal" approach.

One may abandon altogether the cumbersome overhead of the MTD approach with its filters and look-up tables and proceed with a straighforward design for measuring phase. This design may be based on a pair of "AND" circuits.

As might be expected considerable improvement is theoretically available from such a procedure. Without further experience it is not possible to predict if it is feasible to achieve this improvement in practice.

For the case of relatively strong signals the variance, in square radians, of the measurement of phase may be estimated as $(2/n).(N/S)$ where n is the number of cycles in the radar pulse when it is the input to the "AND" circuit, N is noise power and S is signal power.

To derive this rule note that the signal at the phase comparator may be written $\sqrt{S} \cdot \sin(2 \cdot \pi \cdot f \cdot t) + \sqrt{N}$ and that for strong signals only the time at which this sum changes sign determines the value of the phase. The phase error in radians, is seen to be equal to $\sqrt{N}/S$. For each cycle there are two occasions at which the value of the expression changes sign and the square of the phase error is thus $\sqrt{2 \cdot N/S}$ for each cycle. The errors are assumed to be uncorrelated from pulse to pulse. The estimate of variance follows immediately.

Engineering requirements of the comparator circuits limit the number of cycles available from a heterodyned radar pulse to a maximum of about 400. If only signal noise affects the output of the circuits then the standard deviation in phase measurement, for a signal to noise ratio of 10 dB, is expected to be equal to 1.3 degrees.

Turning to equation 2-1 on page 8 and inserting into it values typical of those found in the en route portion of the National Airspace System (subsection 2.2, page 10) one finds expected standard deviations of range rate of the order of 0.3 knots. This calculated deviation is considerably smaller than that observed and reported in Section 3.

As previously mentioned it is not known if such low deviations are attainable in practice and if they are attainable, what cost must be paid for them. The phase comparator considered in this subsection functions on different principles from that of the Moving Target Detector. Thus the preliminary result of the inquiry posed at the beginning of this subsection is that very low deviations may be attained in theory but that almost certainly a considerable development effort will be required to achieve them.

For the immediate future it is believed that it is best to abandon the search for such optimal processing until it can be shown that the suboptimal MTD processing is inadequate for the task of measuring changes in aircraft velocity.

A study of how the use of phase shift data can contribute to the overall goal of improving air safety is underway at the Technical Center as part of project 122-112-080, Advanced En Route Tracker. Reports are anticipated in December of this year and in December of 1983.

3. ACCURANCY AND RELIABILITY OF PHASE SHIFT DATA

3.1 Introduction to Section 3

The principal purpose of this section is to describe the method of making some observations concerning phase shift data and to report the results of these observations. The conditions under which the observations were made are described in subsection 3.2. The data from six flights observed with the Moving Target Detector (MTD) radar were analyzed in some detail and to each flight is dedicated a separate subsection, 3.3 through 3.8.

The section concludes with a model in subsection 3.9 which may be used to investigate quantitatively the usefulness of phase shift data in the en route portion of the National Airspace System.

3.2 Conditions of Observation

The results of this section are based on observations made with the MTD during a test which took place on the afternoon of September 11, 1980. The MTD system had been installed for test purposes at the en route radar site located on a mountain ridge 11 nmi due north of Bedford, Virginia. Relevant parameters concerning this site and the radar transmitter are as follows:

Latitude: 37° 31' 01.7" N
Longitude: 79° 30' 40.7" W
Altitude: 4220 feet
Radio carrier frequency, f: 1285 Megahertz
Pulse repetion frequencies, prf: 417 Hertz (Hi), 345 Hertz (Lo)
Blind speeds: 78 knots, 95 knots
Pulse width: 2.3 microseconds
Peak power: 2 Megawatts
Scan Time: 12 seconds

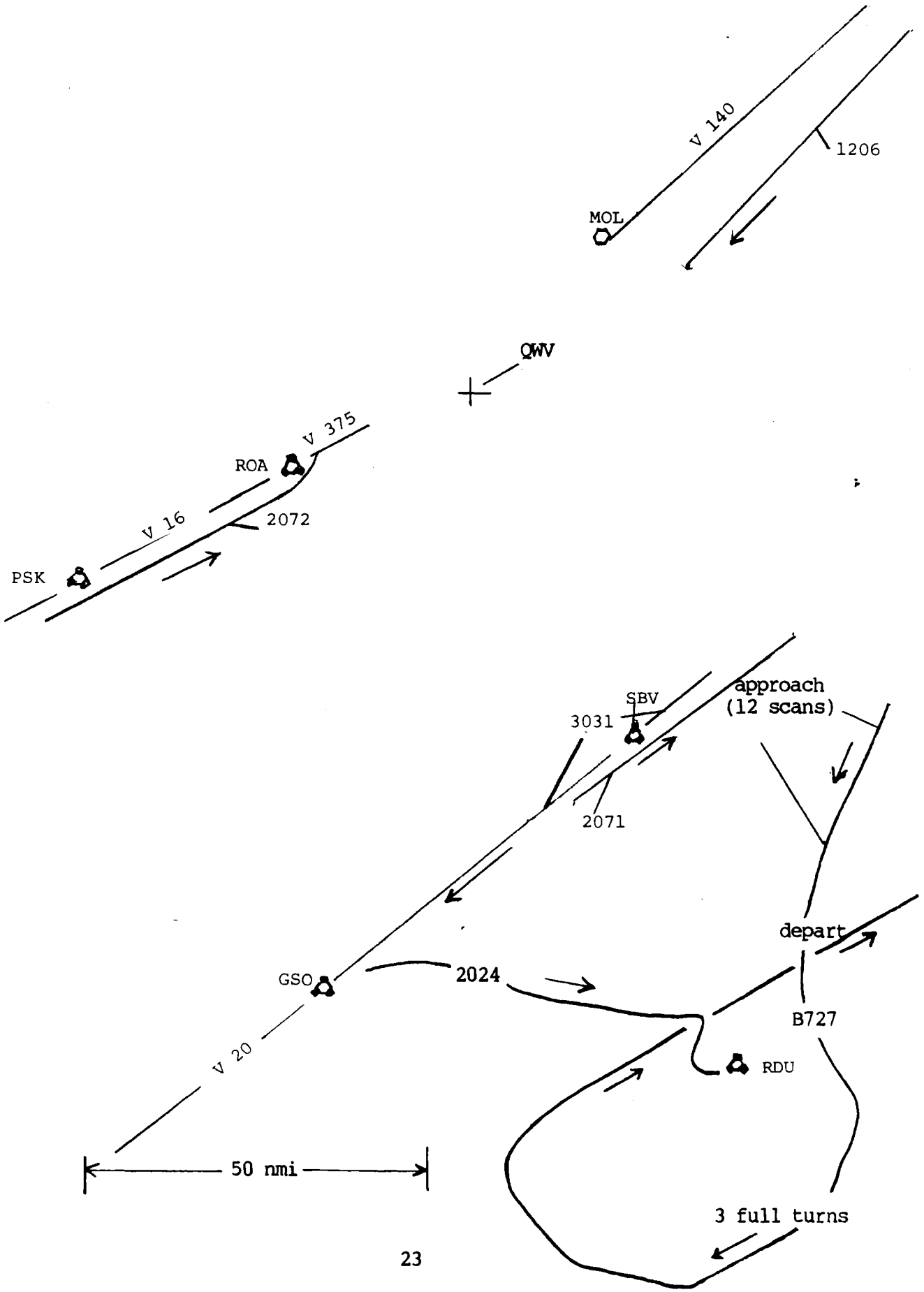
The test was conducted in weather which was generally clear. Its duration was from 1300 EDT until 1500 EDT.

One of the aircraft which was observed was the Department's B727, a large jet transport airplane, which was flown in a special hexagonal shaped pattern (Figure 3-1).

Many other aircraft were also observed as targets of opportunity. Five of these were selected for detailed analysis. These aircraft were navigated generally along straight (non-maneuvering) flight paths.

The following MTD data for all targets were recorded during the test period.

Figure 3-1. This figure illustrates the geometry of the various flights in relation to the Bedford, Virginia search radar. The radar is located near the center of the figure and is labelled QWV. Some of the Vortacs are identified as follows: MOL, Montebello; PSK, Pulaski; ROA, Roanoke; GSO, Greesboro; SBV, South Boston; RDU, Raleigh-Durham. Several Victor airways are also depicted. The test flight path is identified by the symbol "B727". The targets of opportunity are labelled with their four digit octal (beacon) codes. The four flights in the southern part of the figure and the flight labelled 1206 took place in the generally clear piedmont area. The flight labelled 2072 took place over terrain which is part of the Blue Ridge Mountains system and in which ground clutter is to be expected.


V 140
1206
MOL
QWV
V 375
ROA
V 16
2072
PSK
SBV
3031
approach
(12 scans)
2071
depart
GSO
2024
B727
V 20
RDU
50 nmi
3 full turns

MTD scan number
Range, in units of 1/8 nmi (231.5 meters)
Bearing, in ACP units (4096 ACP = 360°)
Target strength, arbitrary units (See subsection 2.5)
Filter numbers, as discussed in Section 2

During the test run secondary (beacon) returns from aircraft were recorded. These consist of:

Beacon scan number, always synchronized with the radar scan
Range, same units as MTD range
Bearing, same units as MTD bearing
Beacon Code, Mode 3/A reply
Pressure Altitude, from Mode C reply

The range and bearing information supplied by the secondary (beacon) system is considered to provide the best estimate of aircraft position. These data are input to a geometric model of the aircraft motion. The model generally assumes non-maneuvering flight by the aircraft. Range rate is calculated from this model and the resultant quantities are compared with estimates of range rate from the phase data. From this comparison the precision associated with the phase data is inferred.

The precision of the data is expressed in terms of the standard deviation, the square root of the variance. The variance is always referred to the true phase shift or true range rate. Thus the deviation as measured in phase cannot be greater than 180 degrees. On the speed scale the deviation cannot be greater than the blind speed. In practice no difficulty is anticipated with any of the "aliasing" effects.

In subsections 3.3 through 3.8 following there is presented relevant data received from the radar returns from the DOT/FAA test aircraft and from returns from five targets of opportunity.

The five targets of opportunity were selected from several hundred available based on speed (turbojet powered aircraft were not desired) and duration of observation (a comparitively long observation time was desired). The purpose of reducing data from these targets was to estimate the accuracy and availability of phase data associated with returns from smaller airplanes.

The same data associated with larger airplanes was taken from observation of the Department's B727 as it proceeded through its test flight. No observations were taken on aircraft which are not airplanes; e.g. helicopters or balloons.

In Figure 3-1 the geometry of the six flights in relation to the radar sensor is presented graphically. An outline of these flights may be presented as follows:

Aircraft squawks	Times observed (EDT) (start-stop)	Remarks
3031	1320-1345	201 knots, 9000 feet altitude
2071	1334-1347	174 knots, 8700 feet altitude
2743	1352-1458	B727 test flight
2024	1358-1419	GSO to RDU, 158 knots 8800 feet altitude
2072	1413-1431	185 knots, 11,400 feet altitude
1206	1446-1512	126 knots, no altitude data

In the following subsections the data for each flight are discussed the order indicated.

3.3 Aircraft Squawking 3031

An aircraft is squawking 3031 and is cruising at 9700 feet pressure altitude southwest along airway V 20 (Figure 3-1). Its speed is 201 knots in a direction generally 234 degrees from true north. It is in view of the search radar from scan 130 at 1320 EDT until scan 230 at 1340 EDT. The aircraft covers a distance of 68 nmi during this time period. The reliabiltiy of range rate data for the portion of the flight in which the aircraft is viewed by the search radar may be summarized as follows.

	High prf			Low prf			Total	
Scans	Hi prec	Lo prec	m	Hi prec	Lo prec	m	m	No Hi prec
101	67	13	21	76	8	17	9	15

This summary is interpreted as follows. The aircraft was observed over a total of 101 scans. While the MTD was transmitting at the high prf (recall the prf shifts by 20% every eight pulses) observations were available with high precision for 67 scans and with low precision for 13 scans. (For the meaning of high and low precision in this context see subsection 2.5 on page 15.) For 21 scans no observation was available from the high prf interrogations.

Similarly during low prf interrogation there were high precision observations for 76 scans and low precision observations for 8 scans. No observations were available for 17 scans from low prf interrogations.

The last two entries in the line of figures refer to the combined results of high prf and low prf interrogations. Of the 101 scans no target was observed during 9 of them. During 6 of the remaining 92 scans only a low precision type observation was available. Put another way during 101 scans there were 15 instances where the MTD system reported no high precision estimate of range rate.

The accuracy of the range rate data for the flight of this aircraft is estimated semi-graphically as follows. The beacon reports are plotted and from these the essential parameters of the flight were measured. Speed was determined to be 201 knots. Heading was approximately 234 degrees, but close inspection of the plotted reports revealed slight adjustments in the flight path. Best estimate of the true flight path consist of a path consisting of three seqments with speed of 201 knots and other parameters as follows:

Scan	Impact parameter
130-142	not modeled
143-152	56.125 nmi
153-170	55.125
171-213	54.05
214-222	not modeled
223-230	65.21

The impact parameter is the distance of closest approach which the projected flight path makes to the sensor. Taken with aircraft speed, the two parameters determine the aircraft range and range rate along a great circle flight path. The range rates computed with the aid of the model are compared with those observed from phase shift data.

Aircraft motion was not modeled for scans 130-142 because the data were missing and the aircraft appeared to be maneuvering. The aircraft appeared to be maneuvering also during scans 214-222.

For the remaining 79 scans there were 73 instances in which one may compare the estimates of range rate expected fom the model with estimates of the same quantity observed from phase shift. The standard deviation between the two quantities was 2.3 knots. This corresponds to a standard deviation in the estimate of phase shift of 9°.

3.4 Aircraft Squawking 2071

The aircraft squawking 2071 also was observed cruising along airway V 20 (Figure 3-1). In this case it was moving northwest at a pressure altitude of 8700 feet.

Cruise speed is 174 knots, direction 54 degrees. The aircraft is in view of the search radar from scan 200 at 1334 EDT until scan 266 at 1347 EDT. Length of flight path is about 38 nmi.

The reliability of range rate data for the portion of the flight in which the aircraft is viewed by the search radar is as follows (for an example meaning of the meaning of the data see the previous page).

	High prf			Low prf			Total	
Scans	Hi prec	Lo prec	m	Hi prec	Lo prec	m	m	No Hi prec
67	54	3	10	58	1	8	7	8

Reliability of high precision data for this flight is thus 88%.

It should be noted that practically all of the missing reports are associated with the portion of the flight when the velocity vector of the aircraft is perpendicular to the vector to the sensor (the flight path is tangential). At this time the range rate is low, less than 8 knots, and the expected response is expected to be strongest in the zero velocity filter. Of the seven misses by the MTD, six of them occur when range rate is less than 8 knots.

In order to determine the precision of the phase shift data for determination of range rate, the aircraft motion was modeled assuming a speed of 174.34 knots and a path with minimum approach to the sensor of 56.375 nmi. These parameters are assumed to be those of the motion of the target.

Calculated range rates vary from -72 knots at scan 200 through zero at scan 244 to 39 knots at scan 266. Thus the expected phase shift varies over the range from -274° through zero to 148° for the low prf interrogation and over the range from -331° through zero to 179° degrees for the high prf interrogation.

The observed deviation in range rate between that predicted by the model and that observed by phase shift data using the methods of subsection 3.2 is 3.9 knots (15 degrees in phase) for the high prf interrogations and 4.2 knots (19 degrees in phase) for the low prf interrogations. These results are for the high precision data only. It has already been remarked that the reliability of this kind of data is 88% for this flight.

The results of this subsection 3.4 are considered representative of those to be expected from the observation of medium performance (175 knot, 10,000 ft altitude) propeller driven aircraft.

3.5 B727 Data

The B727 is typical of large transport aircraft. In the test on September 11, 1980, one of the Department's B727's was flown in a special flight pattern designed to probe the use of the phase data in determining maneuvers (Figure 3-1 on pages 22-23). Accordingly only a part of the B727 flight can be used as a data base for directly determining phase shift accurancy.

The B727 was in view of the MTD radar from scan 289 through scan 616. The times of day are from 1352 EDT until 1458 EDT.

MTD data were available as follows:

	High prf			Low prf			Total	
Scans	Hi prec	Lo prec	m	Hi prec	Lo prec	m	m	No Hi prec
328	268	49	31	267	35	26	12	21

Thus at least one high precision phase shift datum (subsection 2.5) is available for 307 of the 328 scans. The availability of phase shift data is thus estimated to be 94% for this type of aircraft.

The availability of these data is not uniform in phase space. As discussed in subsection 2.3 (page 10), the criterion for declaring a target in filter zero is different from that of the other seven filters. The experience with the B727 data is that there is little high precision response when the absolute value of pulse to pulse phase shift is less than 25 degrees. Practically all of the low precision data are associated with the zero velocity fitler.

Although the B727 was flown in such a manner that an estimate of range rate from beacon reports is difficult to make, there are two separate parts of the flight where the aircraft is on a steady course for a period of 12 scans (144 seconds). From the range rate data associated with these scans an estimate of the deviation of phase shift data has been made.

The B727 maintained a constant speed and heading during a twelve scan part of the approach shown in Figure 3-1. The best fit to the flight path during this period is a great circle flight at a speed of 462.3 knots. The minimum distance of the extended flight path from the sensor is 73.6 nmi. Using these data in a model, the range from the sensor varies from 77.98 nmi to 85.12 nmi. The aircraft range rate is increasing from 140.0 knots to 213.8 knots.

The 12 scans of observations resulted in 12 phase shifts associated with the high prf and 12 associated with the low prf.

Ten of the twelve data points associated with the high prf were of high precision. The standard deviation of the measurement of range rate was 1.5 knots. Similarly ten of the twelve data points associated with the low prf were of high precision. The standard deviation of the range rate in this case was 1.1 knots.

There was another group of twelve scans when the aircraft maintained a steady speed and direction. This was after it turned away from the approach and was following first leg of the irregular hexagon which

forms the flight path. The standard deviation of the measured range rate during these twelve scans was 1.2 knots. The phase shift for this part of the flight was fixed at 233° for the high prf interrogations and 222° for the low prf interrogations.

For further details concerning this flight see Reference 6.

3.6 Aircraft Squawking 2024

The aircraft squawking Mode 3/A code 2024, is apparently on a flight from Greensboro, North Carolina (GSO) to Raleigh-Durham airport (RDU). See Figure 3-1 on pages 22-23.

The aircraft appears on radar about 3 nmi east of GSO at 1358 EDT climbing from a pressure altitude as inferred from the Mode C code, of 2300 feet at a speed of 158 knots. The aircraft climbs to a cruise altitude of 8800 feet, gradually accelerating to 230 knots. The letdown is to the west of RDU where the speed is slowed to 130 knots on the approach to runway 5 at the Raleigh-Durham Airport.

From the climb, cruise and descent characteristics of the aircraft it is assumed to be an excutive twin engine aircraft or a high performance single engine aircraft.

The speed and heading changes associated with the flight are so numerous that good measurements of range rate cannot be made from the range/bearing reports.

The availability of phase data for this flight is as follows:

	High prf			Low prf			Total	
Scans	Hi prec	Low prec	m	Hi prec	Low prec	m	m	No Hi prec
106	48	18	40	56	14	36	29	37

For this case it appears that the availability of high precision phase shift data is 65%. Recalling that the entire flight took place at an altitude below 10,000 feet at a distance of 80-100 nmi from the sensor, this is probably a reasonable estimate of data availability for the conditiions.

3.7 Aircraft Squawking 2072

An aircraft cruising at 185 knots during scans 393 through 481 (1413 EDT until 1431 EDT) was observed by the MTD radar. Its pressure altitude was 11,400 feet and its route of flight was essentially directly towards the radar sensor. The flight path becomes visible on the search radar at a point about 5 nmi south of

Pulaski, Virginia (71 nmi from the radar site). The aircraft cruises along a heading of 060, somewhat south of V 16 and V 375. Analysis of the data is from the initial discovery near Pulaski, Virginia until the aircraft enters the radar come of silence, about 10 nmi from the radar site.

The data of this flight are illustrative of the difficulty to be experienced with the MTD when data are expected in filter zero. The speed of the aircraft is approximately 185 knots and the range rate in this case is essentially -185 knots. Using the parameters of the MTD radar for the high prf interrogations, the expected phase shift of the response is -704 degrees, equivalent to a principle value of 16 degrees. A phase shift of 16 degrees is expected to result in a response principally in filter zero with some response power in filter one, the power ratio being about 1/1000. Indeed some difficulty with the high prf interrogations has been experienced with this flight as is shown by the following availability data:

	High prf			Lo prf			Total	
Scans	Hi prec	Lo prec	m	Hi prec	Lo prec	m	m	No Hi prec
89	42	25	22	70	10	9	5	9

The availability of high precisions data for the high prf interrogations is measurably lower than that for the low prf interrogations. The overall availability of high precision data is 90%.

The aircraft motion was modeled assuming a straight line cruise from scan 391 through scan 462. At scan 463 the aircraft makes a turn of about 15 degrees left. For the non maneuvering path of 72 scans (14 minutes) the standard deviation in measurement of the speed is 3.9 knots on the speed scale. This corresponds to a standard deviation in phase of 18 degrees.

The responses to the high prf interrogations are essentially useless throughout most of this period. Except after scan 451, when the ranges rate drops to a value greater than -179 knots (absolute value less than 179 knots), the errors in range rate measurement are high. Overall the standard deviation of range rate measurement for high precision high prf data is 26 knots, corresponding to a deviation in phase measurement of 98 degrees.

From the data of this flight it is believed that accurate phase shift measurements for this type of aircraft, presumably a comparatively small, propeller driven airplane, are unreliable when the pulse to pulse phase shift is in the range -47 degrees to 47 degrees (range rate between -13 knots and 13 knots). Phase shifts of this size are associated with responses in filter zero. The Moving Target Detector is not a very good detector of aircraft when speeds are within 13 knots of the blind speed (but see the remarks on the bottom of page 33).

At pulse to pulse phase shifts of 238 degrees to 273 degrees, on the high prf interrogation frequency, the standard deviation in measurement of phase shift was measured as 18 degrees, corresponding to a standard deviation in range measurement of 4 knots. The value of this standard deviation is comparable to that found elsewhere for propellor driven aircraft (subsections 3.4 and 3.8).

3.8 Target of Opportunity Squawking 1206

An aircraft was observed cruising somewhat south of V 140 in a generally southwest direction at a speed of 126 knots. It was squawking code 1206 on Mode 3/A and it was not squawking altitude.

This aircraft generally followed the 54 degree radial defined by the MTD radar and a model was prepared with the assumption that the range rate was invariant. The average range rate of this aircraft was -124 knots and this is assumed to be its true range rate.

The data for the aircraft consist of reports from scans 561 through 691, from 1446 EDT until 1512 EDT. This corresponds to 131 scans covering a period of 26 minutes. At the start of the data the aircraft's range and bearing location was 91-5/8 nmi, 582 ACP (51°). At the finish the location was: range, 37-3/4 nmi; bearing, 686 ACP (60°). See Figure 3-1.

Although one might expect some improvement in data quality as the aircraft approaches the sensor, due to a presumably increased signal to noise ratio, the data were not sufficiently precise to demonstrate such an effect. The quality of the MTD reports for these scans is shown by the following distribution:

	High prf			Low prf			Total	
Scans	Hi prec	Lo prec	m	Hi prec	Lo prec	m	m	No Hi prec
131	106	2	23	96	17	18	8	13

The reliability of high precision range rate reports for this aircraft is thus 90%.

The model assumes a constant range rate of -122 knots, corresponding to a phase shift of 248 degrees for the low prf interrogations and a phase shift of 146 degrees for the high prf interrogations.

The variance from these quantities has been calculated for the available data. The standard deviation for the high prf data is 15 degrees, corresponding to a standard deviation in range rate measurement of 4 knots.

Similarly for the low prf data the standard deviation in phase measurement is 19 degrees. Because the blind speed for the high prf interrogation is higher than that for the low prf interrogation, the standard deviation in range rate for the high prf interrogation is also 4 knots.

Recalling that the data refer to an aircraft which is not necessarily cruising at constant speed or direction, the deviations which are measured may be taken as upper limits on those available for this type of aircraft at these phase shifts.

3.9 Proposed Model of Reliability and Accuracy of Phase Shift Data

The reliability and precision of phase shift data are estimated from observations of airplanes made during a two hour period within the surveillance area of MTD radar. There was no weather clutter observed and the observations were made in an area which was generally free of ground clutter.

There were observations made on a single large aircraft, a B727, following the track of a special test pattern during a period of approximately one hour. In addition, data corresponding to the tracks of five smaller aircraft were studied. Total observed time for the smaller aircraft was approximately two aircraft-hours. The results of the observations are summarized assuming that the B727 data are typical of the larger transport category aircraft and that the other data are typical of airplanes in the general aviation fleet. It is convenient to present them in the form of a model.

For larger aircraft the overall availability of high precision phase shift data approaches 100% except when the pulse to pulse phase shift is low. A high precision datum is not generally available if the absolute value of pulse to pulse phase shift is less than 25 degrees.

The precision of phase shift data associated with B727 size aircraft is such that the estimated standard deviation of range rate accuracy is 1.2 knots. This corresponds to a standard deviation in the pulse to pulse phase estimate of 5 degrees.

For smaller aircraft the numbers suggest somewhat poorer results. In these cases the MTD is relatively insensitive to pulse to pulse phase shifts of less than 40 degrees. Overall availability of high precision phase shift data is about 90%. The standard deviation of range rate measurements appears to be about 4 knots or, on the phase scale, about 18 degrees.

It is believed that the models described here are valid for aircraft similar to those specified. By availability is meant availiability for low prf and high prf interrogations separately. In this sense an aircraft is interrogated twice for each scan.

1. Aircraft similar to the B727

   Avilability if pulse to pulse phase shift (absolute value), is less than 25 degrees
   Probability of high precision response 0.33
   Probability of low precision response 0.40
   Probability of miss 0.27

   Availability if pulse to pulse phase shift (absolute) value is greater than 25 degrees
   Probability of high precision response 0.86
   Probability of low precision response 0.07
   Probability of miss 0.07

   For high precision responses the standard deviation of the measurement of pulse to pulse phase shift is taken as 5 degrees for this kind of aircraft.

   Low precision responses may be ignored.

2. Propeller driven general aviation aircraft

   Availability if pulse phase shift (absolute value) is less than 40 degrees.

   Probability of high precision response 0.06
   Probability of low precision response 0.11
   Probability of miss 0.83

   Availability if pulse to pulse phase shift (absolute value) is greater than 40 degrees.

   Probability of high precision response 0.77
   Probability of low precision response 0.13
   Probability of miss 0.10

   For high precision response the standard deviation of the measurement of pulse to pulse phase shift is taken as 18 degrees for this kind of aircraft.

   Low precision responses may be ignored.

It may be possible to reduce these deviations by improved processing at the radar site (subsection 2.6 on page 16).

It is important to keep in mind that the data on which this model is based are from observations taken over a period of two hours during one day. They are expected to be representative of results expected with the MTD in the National Airspace System.

The somewhat disappointing results of this test when phase shift is near zero and strong returns are expected in filter zero, the zero velocity filter (ZVF), may be misleading. There are unpublished data which seem to contradict the results of this section with respect to small values of phase shift. Such data, from observations made on a later occasion (December 5, 1980), tend to show that the reliability of aircraft detection when replies fall in the ZVF is not significantly different from that when the replies fall in the other filters. It is therefore possible that the adjustments to be made for the zero velocity filter were only approximately correct during the test of September 11 and that the model reported in this subsection is unduly pessimistic with regard to the zero velocity filter.

The results presented herein may be taken as generally poorer than those which can be made available in an operational system. There are errors, unavoidable in the present analysis, which are included in the model which are due to: (1) improper preparation of the table for reducing filter data to phase shift data (Table 2-2) and (2) improper measurement of the true target range (ATCRBS precision). These errors are not believed to be large but they will have an adverse effect on precision.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions.

The availability and precision of pulse to pulse phase shift data were measured using the Moving Target Detector (MTD) system. This measurement was performed using L-Band radar on airplane targets typical of those found in the National Airspace System. For non-zero velocity filters, where pulse to pulse phase shift is greater than 25 degrees, the availability is above 90% and the standard deviation of the phase-shift is between 5 degrees (large aircraft) and 18 degrees (small aircraft).

For the zero velocity filter, where pulse to pulse phase shift is less than 25 degrees, the availability was observed to be lower. This conclusion for the zero velocity filter is suspect and seems to be contradicted by data as yet unpublished.

Pending the results of work now in progress at the FAA Technical Center, the approach making use of the MTD to provide phase shift data, although not optimal, may be considered adequate. Other approaches are probably capable of providing increased precision but costs and risks associated with their development are unknown.

Phase shift data can be made available in a timely manner to a processing system (tracker) which can use these data to better predict the motion of airplanes in the short term (2 minutes). With such availability aviation safety will be enhanced by improved operation of the Conflict Alert system.

4.2 Recommendations

Three recommendations are proposed.

First, investigate the usefulness of phase shift data towards the general solution of the problem of predicting aircraft motion over the short term (2 minutes).

For the en route system this recommendation already is being carried out at the FAA Technical Center under subprogram 122-112-080 (Advanced En Route Tracker) and reports are expected over the course of 1982-1983.

For the terminal system the use of phase shift data was examined and discarded in 1977 (Reference 9). The principal argument against range rate processing is dependent on an estimate of 15 knots as the standard deviation of its measurement. For the long range sensor this appears to be a gross overestimate (Section 3). The work on the terminal system should be reconsidered with a more realistic estimate of the expected standard deviation of range rate.

Secondly, a study of the costs and benefits of adding phase measuring search radar to the National Airspace System should be undertaken. Much of the benefits can probably be worked up from the scheduled Technical Center reports. A thorough cost estimate on this radar has not been performed. There is an MTD Implementation Study (February 1976) in which a figure of $95,000 per MTD channel is quoted but this can only be used as a starting point.

Third, if the results of the cost/benefit study are favorable, implement velocity measuring (phase measuring) radar and appropriate software as an operational part of the National Airspace System. The date for deployment should be scheduled for sometime soon after 1988.

APPENDIX

Lag of Calculated Velocity Vector (Page 5)

The tracker used in the en route portion of the National Airspace System (NAS) is similar to that proposed by N. Levine (Bell System Technical Journal, pp 821-840, May 1961). Such a tracker attempts to estimate velocity by effectively averaging target position reports over a number of previous scans and assuring that acceleration is zero (no turn).

The number of such scans, n, is related to the velocity smoothing constant, ß, by the equation

$$ß = 6/(n \cdot (n+1)).$$

In the non-maneuvering mode of the NAS en route tracker, the one used for shallow turns such as those described in the example of subsection 1-1, the value of ß is equal to 3/64.

Inserting this value into the equation, it appears that data from the most recent 11 scans are used to determine velocity. One may show graphically that in the example this is equivalent to permitting the calculated velocity vector to lag the true vector by 33°.

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