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PROMPT DETECTION OF AIRCRAFT MANEUVERS BY USE OF RANGE RATE RAD--ETC(U)
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Prompt Detection of Aircraft Maneuvers by Use of Range Rate Radar Data

Dr. James A. Shannon

August 1981

Final Report

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16. Abstract In addition to the usual range and bearing information concerning aircraft targets, the next generation of long range radars can have the capability of measuring directly a component of velocity. An investigation was conducted to determine first, the accuracy with which target velocity can be measured and secondly, how these velocity data can be exploited so as to better predict aircraft position.

A B727 was flown in a special pattern, which included many maneuvers, at a distance of about 100 nmi from a prototype of the velocity measuring radar. The standard deviation of the measurement of the component of velocity was found to be less than 1.3 knots.

The velocity data from the test flight were subjected to processing by a tracker which calculates changes in aircraft heading from changes in velocity component. The results are promising. In all maneuver were immediately detected and the velocity vectors constructed by the tracker followed closely the vectors flown by the aircraft.

The benefical consequences of incorporating a tracker using velocity data are pointed out. An example is given comparing the automatic of a potential conflict using the conventional tracker and then the tracker which processes velocity data. In the example the use of such data is vital to a safe resolution.

Appropriate recommendations are included in this Report.

17. Key Words
Doppler, Maneuver Detection, Turn Detection, Radar, Range Rate, Single Look Speed Measurement

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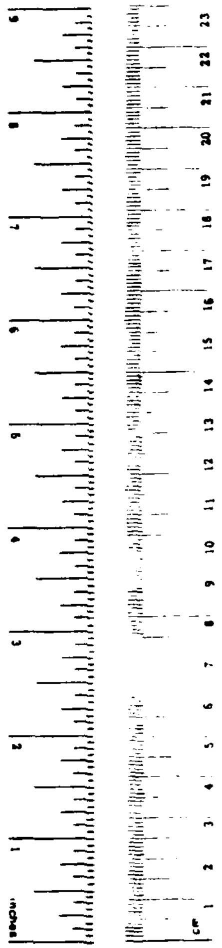
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

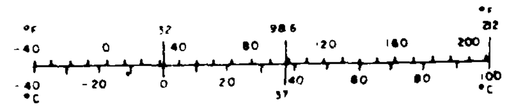
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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 General

The Moving Target Detector (MTD) type of long range radar is described at length in Moving Target Detector-II Summary Report, FAA-RD-80-77. It can be deployed in the en route portion of the National Airspace System beginning in 1988. Besides the conventional information consisting of target range and target bearing the MTD is able to measure another parameter: range rate. A brief investigation was made to determine if range rate data can be useful in tracking of aircraft targets.

The conclusion of this report is that such data can be indeed useful in an automatic tracker and that efforts should proceed so that an automatic tracker which is capable of using range rate data can be ready for use in the National Airspace System when the data become available.

The remainder of this introductory section is devoted to an overview of the concept of range rate processing and of how it is incorporated in the MTD radar. It is shown how the MTD processor determines the pulse to pulse shift in phase of target returns and how, from this shift, the target range rate can be determined.

The description of a test flight designed to provide a data base for testing the usefulness range rate data in the en route system is described in Section 2 following.

In Section 3 the results from this flight are summarized. The blip to scan ratio is determined for the test flight as is the precision with which one can measure range rate with the MTD radar.

In Section 4 the data base developed from the test flight is used in a "nominal" automatic tracker. It is shown how this tracker is able, with the use of range rate data, to follow the velocity vector of the tracked aircraft through various maneuvers. The most important results of this report are contained in Table 4-1 on page 34 and in the accompanying discussion of subsection 4.4 (page 33). In the Table the extent of each maneuver as calculated by the nominal tracker is compared with the extent observed from plotted data.

A summary and the conclusions of the investigation are contained in Section 5. The immediacy with which a tracker based on range rate data can follow aircraft maneuvers is emphasized and safety aspects of such a tracker, particularly with respect to automatic detection and resolution of potential conflicts, are remarked on.

1.2 Origin of Range Rate Data

To prevent confusion it is well to point out at the outset that the Moving Target Detector (MTD) radar does not depend on the Doppler effect in its processing. For aircraft targets the Doppler effect is very small, rarely amounting to a frequency shift of more than two parts in a million. This shift in frequency plays no part in the following analysis of the MTD radar system. At most it can shift the received phase of a target report by 0.36 degrees. The measurement precision of phase shifts in the MTD does not allow shifts of such magnitude to be detected.

The MTD detects targets by transmitting a series of pulses containing radio frequency energy and noting the time delays associated with the echoes. The echoes contain phase information as well as amplitude information. If the target is moving in a radial direction relative to the radar transmitter/receiver the received echo will have its phase shifted with each pulse according to the following rule:

$$\text{Phase shift} = 720^\circ * (r/c) * (f_o/\text{prf}),$$

where r is the radial speed, c is the electromagnetic velocity, f_o is the radio frequency of the radar and prf, the pulse repetition frequency, is the reciprocal of the time between pulses.

Fundamental to this type of detection is the concept of blind speed where the pulse to pulse phase shift is an integral multiple of 360°. The blind speed is thus an integral multiple of:

$$(c/2) * (\text{prf}/f_o).$$

In the Moving Target Detector type of long range radar system, pulses are transmitted in groups of eight and the radar returns are processed digitally. The eight in-phase and quadrature returns from a given range all are treated as a set of eight complex numbers. These are processed through eight digital filters. The output of each filter depends on pulse to pulse phase shift as well as target strength.

It will be shown in the following subsection how, working from filter ouputs, one may determine the pulse to pulse phase shift.

1.3 Determining Phase Shift

A target response is classified into one or more of eight filters by the MTD processing subsystem. If a target responds in one filter only the response is referred to as a low precision response. The reason for this nomenclature will be explained in subsection 3.2.2, (page 12). The phase shift assigned to the target for a low precison response is given by the peak response of the filter. The response is as follows.

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

In the more usual case a target responds in two or more filters. This is called a high precision response. In this case only the response corresponding to the strongest filter and that in a neighboring filter are considered. To determine a phase shift enter Table 1-1 on the next page with the power ratio of the strongest neighbor response and of the strongest response. Read off the phase shift from the Table.

Table 1-1 was constructed from the response curves of the filters of the MTD. These curves are Figures II-3a, II-3b, and III-3c of Moving Target Detector-II Summary Report, FAA-RD-80-77 (1981). This Report is also published as Report ATC-95 by Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts.

As an example of the use of Table 1-1 consider the response of the MTD to a "typical" target. The response in filters 5,6 and 8 is negligible. The response in the other five filters is as follows:

Range (1/8 nmi)	Bearing (ACP)	NSTR	Filter
873	535	44	1
873	535	101	2
873	535	148	3
873	535	79	4
873	536	78	1
873	536	182	2
873	536	276	3
873	536	156	4
873	536	15	7

In the first column is reported range in units of 1/8 nmi. In the second column is listed the bearing in ACP (4096 ACP = 360° of arc = 2π radian). In the third column is normalized target strength, proportional to the square root of the power received from the target. The filter corresponding to the appropriate range, bearing, and strength is listed in column four.

This particular target has returns in five filters with the power returned in each filter distributed as shown on page 5.

TABLE 1

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 Strongest in Filter	Response Next Strongest	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

Filter	Power	Power
1	$44^2 + 78^2 =$	8,020
2	$101^2 + 182^2 =$	43,325
3	$148^2 + 276^2 =$	98,080
4	$79^2 + 156^2 =$	30,577
7	$15^2 =$	225

The strongest response is associated with filter 3 and in filter 2 is found the next strongest response. The power ratio of the response is equal to the ratio of these responses, 43,325 divided by 98,080 or 0.442. Entering Table 1-1 with these numbers it is found that the appropriate phase shift for this target is equal to 135°.

1.4 Numerical Values

In the prototype MTD radar system reported herein the radio carrier frequency is 1285 MHz. There are two pulse repetition frequencies (prf): a low frequency of 345 Hz and a high frequency of 417 Hz. Radar energy is transmitted first in the form of a series of eight pulses with a prf of 345 Hz (time separation between pulses of 2.9 msec) followed by a series of eight pulses with a prf of 417 Hz (time separation of 2.4 msec).

There are thus two blind speeds, a Low Blind Speed of 78.283 knots and a High Blind Speed of 94.621 knots.

The radar antenna rotates at a rate which results in 12 second scans.

1.5 Interpreting Phase Shift Information as Range Rate

A phase shift measurement standing by itself determines a radial speed (range rate) only to an integral multiple of the blind speed. Thus a phase shift of 135° on a low prf response corresponds to a basic range rate of 29 knots ((135°/360°) * 78=29). This phase shift is also compatible with range rates of 108 knots (29+78), of 186 knots (29+(2*78)), of 264 knots (29+(3*78)), and so forth. Negative range rates associated with a phase shift of 135 are: -49 knots (29-78), -127 knots (29-(2*78)), etc.

Ordinarily the radar sensor detects a pair of phase shifts corresponding to the low and high pulse repetition frequencies (prf). Since the two prf differ by 20%, any ambiguity in determining range rate is usually readily resolvable. If, for example, one finds a phase shift of 135° for the low prf response (78 knot blind speed) and a phase shift of 236° for the high prf response (95 knot blind speed), then one is given the choice of range rates shown on the following page.

For 78 knot blind speed	For 95 knot blind Speed
-440 knots	-411 knots
-362	-317
-284	-222
-205	-127
-127	- 33
-49	62
29	157
108	251
186	346
264	441
344	
421	
499	

If one knows that the aircraft is moving away from the sensor, then the only reasonable choice of range rate is 345 knots. This range rate is compatible with the measurement of 344 knots for the 78 knot blind speed and with the measurement of 346 knots for the 95 knot blind speed.

It may be noted in this example that a range rate of -127 knots is also compatible with the phase shift data. In practice a reasonableness check is almost always available to make the final determination. In the example the scan to scan shift in range was 1-1/8 nmi, confirming the 345 knot value for range rate. A range rate of -127 knots would require an entirely different range shift, one of -3/8 nmi.

TEST CONDITIONS

2.1 General

A flight designed to provide a data base for testing the use of range rate data in the en route portion of the National Airspace System was flown on September 11, 1980. The duration of the flight was from 1:30 p.m. EDT until 2:45 p.m. EDT.

The prototype long range radar MTD system had been installed at Bedford, Virginia for some time. The test aircraft was a B727 which was flown in a special pattern at a distance of approximately 100 nmi from the radar site. Aircraft altitude was FL 350 (approximately 35,000 ft or 7.62 nmi) so that the aircraft was in plain view of the sensor at all times. No weather or ground clutter was present in the flight test area.

Colocated with the search radar was a radar beacon transmitter/receiver. The test aircraft was identified by its discrete beacon code and a 3 nmi square box was constructed about the beacon position of the test aircraft. All primitive targets within this box were reported and can be analyzed (subsection 2.3 on page 9).

2.2 Flight Pattern

The flight pattern is the irregular hexagon shown in Figure 2-1. It consists of six straight legs and six turns. Two of the turns are nominally 90° turns and four of them nominally are 45° turns. All turns are at a nominal bank angle of 30°.

The Figure shows the track of the beacon responses for the entry and for the first hexagon maneuver. The second pattern was similar except that the northeast 90° turn was very much extended, as shown in Figure 4-2 on page 30. The test flight was completed with a third repetition of the pattern.

The flight pattern is designed to test turn detection under various conditions. In principle the easiest turns to detect are the 90° turns when the radial velocity initially changes most rapidly. These are the 90° turns in the northeast. The most difficult to detect are expected to be those the farthest south. Distance is 140 nmi in this case and the change in radial velocity is expected to occur chiefly after the aircraft enters the turn.

The patterns are flown at a distance of between 100 nmi and 140 mni from the radar transmitter. This distance is greater than that normally encountered for targets in the en route system. However it is a reasonable choice of distance since the search radar may be called upon at times to function at distances of 160 nmi.

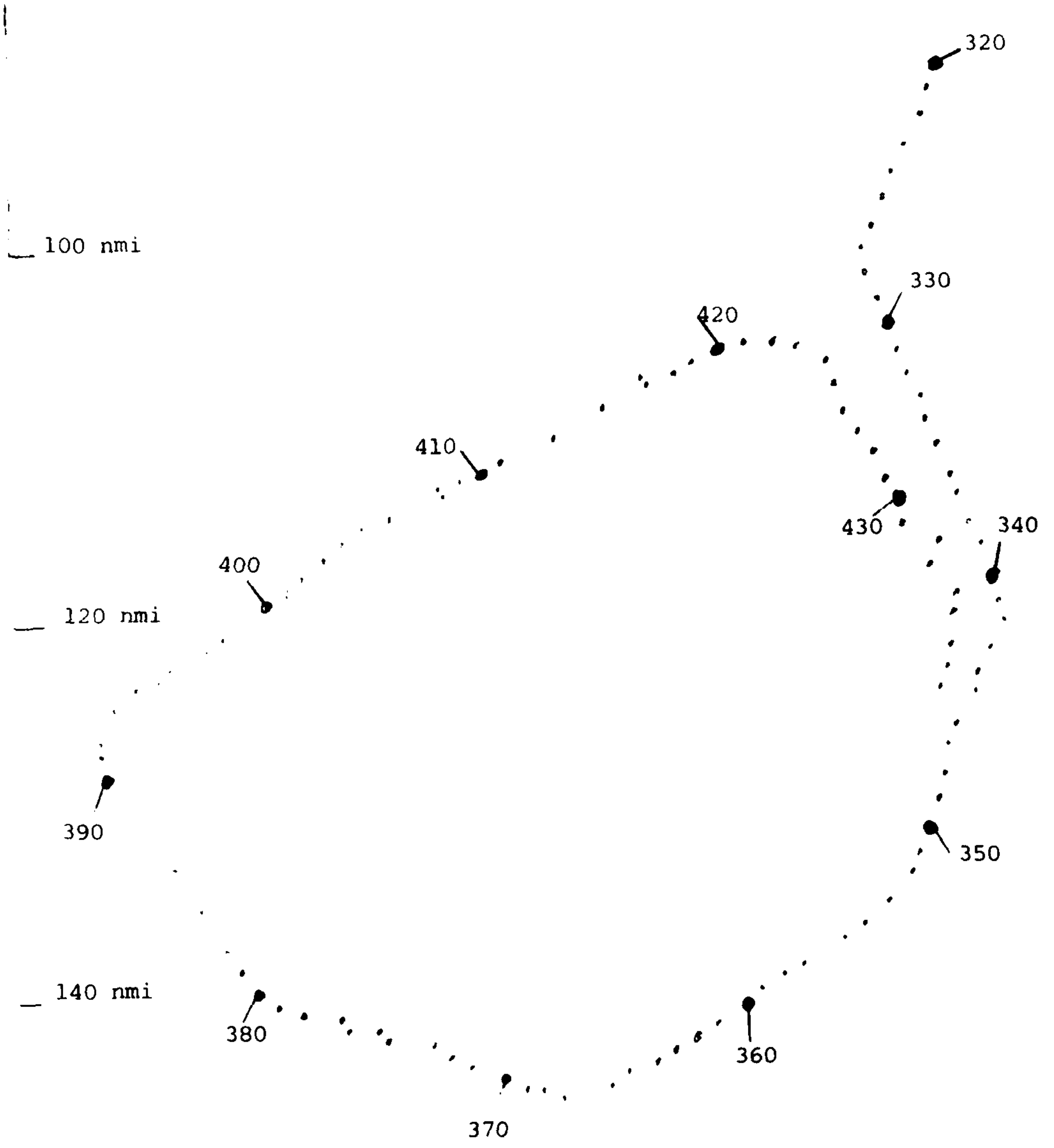


Figure 2-1. Plot of track of test aircraft from scans 320 through 438. The sensor is located directly north of the scale on the left side of the page.

2.3 Data Supplied

The following data concerning the tests are made available. For each scan:

1. Range and bearing of target squawking discrete beacon code 2743. Range is quantized to 1/8 nmi and bearing to 1 ACP (4096 ACP = 360° of arc = 2π radian).

2. All primitive search targets within 3 nmi of the beacon target. These primitive search targets consist of:

    2.1 Scan number
    2.2 Bearing (in ACP units)
    2.3 Range (in 1/8 nmi units)
    2.4 Strength (arbitrary units)
    2.5 Normalized strength (arbitrary units)
    2.6 Filter number if strength is nonzero
    2.7 X and Y coordinates of primitive targets

Data were received from a total of 489 scans. These were from scans indexed as 165 through 258 and 289 through 683. The data from scans 289 through 616 were subjected to especially close scrutiny as during these scans the test aircraft was performing many maneuvers.

3 RESULTS

The overall results of the flight test are briefly summarized in this section.

3.1 Blip to Scan Ratios

Each piece of data returned is placed into one of four classes as follows:

Class A: Returns are present for both high prf and low prf interrogations and in both cases they fall into two or more adjacent filters, i.e. they are both of high precision.

Class B: Returns are present for both high prf and low prf interrogations but at least one set of returns is of low precision, i.e. consists of returns in only one filter.

Class C: Either returns are present for only one filter or no high precision response is available.

Class D: Interference is present in the replies.

The 328 scans of data indexed as scans 289 through 616 were examined with the results that assignment to the four classes were made as follows:

Class A:	206	or 63% ± 3%
Class B:	75	22% ± 2
Class C:	31	9% ± 2
Class D:	2	1% ± 0.4
No returns:	14	4% ± 1

The numbers after the ± sign refer to one standard deviation.

3.2 Accuracy of Range Rate Data

In order to determine the accuracy of the range rate data which results from application, of the methods of subsection 1.3, measurement of aircraft range rate independent of the Moving Target Detector (MTD) system is required. As no special instrumentation was used on the test flight, the positon reports of the Air Traffic Control Radar Beacon System (ATCRBS) constitute the best position data which is available.

In the circumstances of the test the best estimate of range rate generally is provided by the range rate data directly. The ATCBRS reports usually are not precise enough to provide a meaningful estimate of range rate (phase shift) error. However there are two instances where the aircraft appears to have been flown for a significant time period at constant speed over a great circle course. From them some estimates of the precision of range rate data may be inferred.

3.2.1 Scans 329-340

At scan 327 the test aircraft makes a left turn of about 45° and proceeds along a heading of 154°, directly away from the sensor (Figure 2-1 on page 8). During this portion of the flight the aircraft is in a tail on aspect to the sensor.

During the scans 329 through 340 the aircraft moves along a great circle from a distance 102.75 nmi to a distance 118.875 nmi from the sensor. Average range rate for the 12 scans of ATCRBS data is thus 439.8 knots. The phase shift associated with these 12 scans gives an average range rate of 439.89 knots, a variance, for 12 scans of 1.49 knots^2 and a standard deviation of 1.2 knots. It is not known how much of this variance is due to errors not associated with range rate processing. In this case an upper limit on the standard deviation associated with range rate data is 1.2 knots.

These are all high precision responses.

3.2.2 Scans 299-311

Chronologically this portion of the flight test preceded that discussed in subsection 3.2.1. It consists of part of the aircraft approach to the test area. During this part of the approach the aircraft appeared to follow a great circle path of length 53 nmi at a constant speed.

The best fit to the aircraft flight path during this portion of the flight 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 great circle model the aircraft range from the sensors varies from 77.98 nmi at scan 299 to 85.12 nmi at scan 311. During this time frame the aircraft range rate is increasing from 140.0 knots to 213.8 knots.

The 12 scans of observation resulted in 12 phase shifts associated with the 95 knot blind speed and 12 phase shifts associated with 78 knot blind speed.

Of the 12 data points associated with the 95 knot blind speed, 10 consisted of data associated with two or more filters (subsection 1.3) and two of data associated with one filter only. The variance of the ten points associated with two or more filters is 2.32 knots^2 and the standard deviation of this measurement is 1.5 knots. Of the 12 data points associated with the 78 knot blind speed, 10 consisted of data associated with two or more filters and two of consisted of data associated with one filter only. The variance of the 10 points associated with two or more filters is 1.16 knots^2. The standard deviation of the range rate of these data is thus 1.08 knots. These are high precision responses.

The remaining four data points are associated with filter zero only. The variance associated with these four points is 10.49 knots^2 and the standard deviation associated with them is 3.24 knots. These are responses associated with one filter only and are considered low precision responses.

To summarize, range rate measurements associated with high precision responses are expected to have a standard deviation of less than 2 knots. Those associated with low precision responses are expected to have a standard deviation of about 4 knots.

3.3 Extension to Other Conditions

The following three subsections contains brief discussions concerning extensions of the principle results of this report to situations which are similar to but not exactly like those experienced in the test. The situation for smaller aircraft is considered in subsection 3.3.1. In subsection 3.3.2 the effects of clutter, due to terrain and to precipitation, are discussed. In subsection 3.3.3 there is a brief treatment of the situation concerning the shorter range airport surveillance radars.

3.3.1 Aircraft Smaller than the B727

The test aircraft, a B727, is a fairly large one. On the other hand, the distance from sensor to aircraft was generally somewhat greater than that normally encountered in the en route portion of the National Airspace System.

It will be assumed that: (1) the variance associated with the measurement of range rate is a mainly a function of signal to noise ratio, (2) radar cross section is proportional to physical cross section and (3) that the free space laws for radar signal propagation are valid.

Note that the physical cross section of a business jet is about 18% that of a B727. It follows that the energy in the return echo from such an aircraft is equal to that from the test aircraft when the business jet is at a range equal to 65% of that of the test aircraft. This means that the data of subsection 3.2.1 and 3.2.2 concerning the variance of range rate may be assumed applicable to business jets at range of 77 nmi (subsection 3.2.1) and 55 nmi (subsection 3.2.2).

During the flight test the range at which good data become available is 160 nmi. At lesser distances reliable range rate information is available for the B727 test aircraft. Assuming the validity of the specified assumptions, range rate data for a business jet aircraft should be available at ranges out to at least 100 nmi. Normally 100 nmi is the maximum range required in practice of the long range sensors.

The smallest fixed wing aircraft such as the Cessna 150, are expected to have a cross section roughly equal to about 8% of that of the B727 (about 40% that of a business jet). At a fixed range the signal to noise figure for a C-150 size aircraft will be poorer yet than that of a business jet. Assuming the validity of the three assumptions this means that good data for a C-150 type aircraft will be available at least out to 80 nmi and perhaps farther.

3.3.2 Expected Effects of Terrain Clutter and of Precipitation

The Moving Target Detector Radar is designed specifically to function in an environment of strong clutter, whether the clutter is due to terrain or to heavy precipitation.

In principle the result of processing a composite signal, consisting of terrain clutter plus target, is the same as the result when terrain clutter is absent. This is because the processing includes pulse to pulse subtraction of signals in filters one through seven. For filter zero an elaborate mechanism is used to eliminate the effects of terrain clutter. The net result is that the MTD radar is expected to be transparent to the echo from a fixed target in all filters except filter zero. In filter zero great care is taken to match the signal from an aircraft to the processing method so that terrain clutter is rejected.

One may thus anticipate that the MTD radar will function as well with terrain clutter background as it does in the clear.

The action of the MTD in heavy precipitation clutter is less clear. Experimentally, excellent results concerning aircraft detection were observed using short range search radar in heavy rain (L. Cartledge and R.M. O'Donnell, Project Report ATC-69, Description and Performance of the Moving Target Detector, FAA-RD-76-190, March 1977). Nevertheless it would be well to have confirmation of accurate phase shift measurement using the long range MTD radar in a controlled situation, i.e. one where the precipitation contains a strong echo with a significant radial component of velocity.

To summarize, one may expect with come confidence results similar to those reported in subsection 3.2.1 and 3.2.2 when terrain clutter is present. One may entertain the same expectation in the presence of precipitation clutter but with somewhat less confidence.

3.3.3 Extension to Short Range Radars

The substance of this report is concerned with the radars used in the en route portion of the National Airspace System. These normally have a maximum range of 160 nmi. The System also makes use of a large number of radars, operating at frequencies between 2700 MHz and 2900 MHz, for use near airports. These comparatively low powered radars ordinarily are limited in range to 60 nmi.

The next generation of these short range radars, the ASR-9, will have range rate data available. Investigation of the use of range rate data supplied by these radars is not part of this study. Nevertheless some data from a prototype short range MTD radar operating at Lawrence G. Hanscom Field, near Bedford, Massachusetts was made available during November of 1978. A cursory investigation of the precision of the range rate data and of its use in the tracking problem was carried out.

Targets of opportunity approaching Logan International Airport (BOS) at a distance of approximately 20 nmi southeast of the prototype radar were observed.

A target of opportunity approaching runway 33 is on a course headed directly for the MTD radar.

Its range rate, according to range information (not phase shift data) from the Hanscom radar increases, roughly uniformly, over a period of twenty scans (94 seconds), from 118 knots to 134 knots. According to simple processing of phase shift data the range rate is calculated to increase, roughly uniformly, from 124 knots to 134 knots.

A second aircraft was observed on an approach to BOS. Its speed slows down from 222 knots to 126 knots. It performs two left hand turns. Between turns its range rate is approximately uniform. Estimates of range rate from range data are compared with those from phase shift data as follows:

Scans	Range Rate From Range Data	From Phase Shift Data
20-25	46.9 knots	42.2 knots
30-35	57.4	57.2
46-49	-79.8	-69.7
62-64	-111.7	-116.3

The standard deviation between the two methods of measuring range rate is 6 knots. It is not known how much of this deviation is due to errors associated with reduction of data, how much is associated with range errors and how much is associated directly with range rate processing.

4. MANEUVER DETECTION USING RANGE RATE DATA

In this section it will be shown that with the use of range rate data provided by phase shift information it is possible to detect immediately when an aircraft begins a maneuver. It will further be shown that rate of the maneuver (turn rate) can be estimated quantitatively.

It will be shown how the velocity vector calculated with range rate data follows closely the velocity vector of a maneuvering aircraft. The lag between the two vectors, calculated vs actual, usually associated with an automatic tracker can be essentially eliminated.

The safety implications of range rate processing are not discussed in this section but in section 5 following.

4.1 Determining Heading Change Using Range Rate Data

The next generation of long range search radar can have the capability of measuring essentially instantaneously the range rate of an aircraft target (Section 1 above). Combining this datum with aircraft speed it will be possible to measure aircraft heading and hence, aircraft velocity.

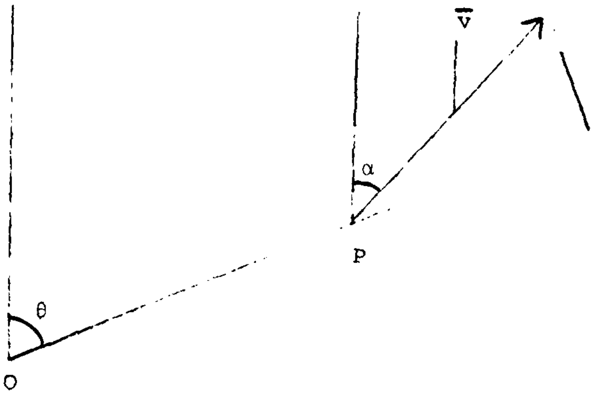
In the present system aircraft velocity is determined by the necessarily slow method of computing differences associated with position reports. These reports accumulate at the scan interval of ten seconds or twelve seconds. The differences in position are smoothed, in effect, over six or fourteen scan intervals. As a result the velocity vector calculated from the data supplied by the various position reports lags considerably behind the true velocity vector of the aircraft. For a complete description of the tracker of the present system see the NAS Configuration Management Document "Automatic Tracking, NAS-MD-321 (April 14, 1980)."

Using the component of velocity directly available from range rate data it is possible to determine heading changes essentially instantaneously. In fact it may be shown that the change in heading of a target is given by the formula:

$$\Delta\alpha = \Delta\theta - dt*\Delta\dot{r}/(r*\Delta\theta)$$

where $\Delta\alpha$ is the change in measured azimuth position, $\Delta\dot{r}$ is the change in range rate, and r is the target range. In practice range, r, is measured directly and the differences, $\Delta\theta$ and $\Delta\dot{r}$ are calculated from successive measurements of bearing and of range rate. dt is the interval time between scans, normally ten or twelve seconds.

(The formula on the preceeding page may be derived using the geometry shown in the following sketch:



$\bar{v}$ is the velocity vector of the aircraft. It makes the angle α with the fiducial direction as shown. The aircraft is located at point P with polar coordinates r, θ. Range rate, $\dot{r}$ is the projection of the value of $\bar{v}$ on the vector from the origin O to target position P. From elementary geometry $\dot{r}/v = \cos(\alpha-\theta)$ and taking differentials one finds

$$d\alpha = d\theta - dr/(v*\sin(\theta-\alpha)).$$

The denominator in the second term is easily seen to be equal to $r*d\theta/dt$. The formula on the previous page follows by substituting differences for differentials.)

4.1.1 Variance and Standard Deviation Associated with Measurement of Heading Changes

Using the expression for heading change displayed in the previous subsection 4.1, it may be shown, using certain assumptions, that the variance associated with the estimate of heading angle change is given by the following sum:

$$2 \text{ Var }(\theta) + 2 \text{ Var }(\dot{r})/v^2*\sin^2 \beta,$$

where v is aircraft speed and is the angle which the velocity vector of the track makes with the vector from the sensor to aircraft. Var ( ) is the variance associated with the measurement of bearing and Var ($\dot{r}$) is the variance associated with the measurement of range rate. The average value of $\sin^2$ is 1/2. On average then, for 400 knot aircraft the variance in heading estimate is:

$$2 \text{ Var }(\theta) + 10.6 \text{ Var }(\dot{r}),$$

where the variance is in ACP^2 if $knot^2$ is used as the unit of measure of range rate variance.

One frequently takes the variance of bearing measurement as 9 ACP^2 and that practise is followed in this subsection, even though this number is probably too large. The specification for the Moving Target Detector radar will probably require that the variance of bearing measurement be less than 4 ACP^2. Further it will be shown in subsection 4.1.2 below that one can calculate quite nicely with bearing differences as small as one ACP.

The range rate variance is expected to be the most important contributor to total heading variance. For class A data the variance associated with range rate data should not exceed 2 knots^2 (subsections 3.2.1 and 3.2.2) so that the standard deviation associated with a heading change is, on average, 6 ACP or 0.6 , for an aircraft cruising at 400 knots. For slower moving aircraft the standard deviation will be higher.

The calculation of heading change breaks down if the aircraft trajectory is such that the track is headed directly toward or directly away from the radar sensor. If the track of a 400 knot aircraft makes an angle of 1 with the vector from the sensor to the aircraft, then the standard deviation of the measurement of heading change is 16 according to the formula on the previous page.

Assuming one is able to measure the direction of the velocity vector of a target then application of the equation on page 17 enables one to estimate heading changes quickly, accurately and with no time delay.

Ordinarily there will be no significant heading errors using this method. However, when the direction of the track velocity vector points essentially directly toward or directly away from the sensor some difficulties may be expected.

In order to test these difficulties and as an example of the practical use of range rate data, the work described in the following subsections was carried out.

4.2 Use of Range Rate Data in Automatic Tracking

The complete data base, consisting of beacon target reports, search target reports and associated range rate information was subjected to processing by an automatic tracker. This tracker is assumed to be able to compute changes in track heading according to the formula of subsection 4.1 (page 17).

Details concerning this processing are contained in subsection 4.3 and subsections thereto. The results are summarized in subsection 4.4.

4.2.1 Automatic Tracking, General

The designer of any automatic tracker is confronted with a set of design parameters to which one may assign values as one sees fit. One of the key tradeoffs, perhaps the most important, is the treatment of the problem of immediacy vs consistency. One may design a "quick" tracker, responding very quickly to supposed track changes or one may design a "slow" tracker which responds more slowly to such changes but one which presents a consistent velocity picture. It is fair to assert that the NAS Stage A tracker described in MD-321 is in the class of slow trackers. It appears that it was originally designed to present a consistent velocity vector on the plan view display used by the air traffic controller. Thus quickness of response is sacrificed for stability and consistency.

The NAS Stage A tracker could be redesigned as a quicker tracker thus lessening delays associated with the conflict alert function. In the process of such redesign the tracker would lose that consistency on the plan view display which is presumed to be important from the human factors point of view.

4.2.2 Nominal Automatic Tracker

The tracker assumed in this section is designed to work with the data gathered in the flight test. As such it is a single sensor tracker and is less sophisticated than one which can be designed for the multisensor environment of the en route portion of the National Airspace System. Results from a multisensor tracker using range rate data should be better than those found in this section.

The nominal tracker is designed to be a slow tracker in the sense of the previous subsection 4.2.1. It is not so slow as the NAS Stage A tracker, but it is not as quick as it can be. It is designed to minimize the differences between plotted headings and final headings associated with the turning maneuvers which were performed in the flight of the test aircraft. More succinctly put, it makes the Table on heading changes, Table 4-1 (page 34) look as good as that Table can be made to look.

The assumed tracker minimizes peak errors and in doing so it is believed to be a good tracker for purposes of human factors. For use as a processor to be used with the conflict alert function it should perhaps be quickened.

The tracker is required to have information as follows for each target report.

(1) Bearing, from the beacon system
(2) Range, from the beacon system
(3) Range rate, from the search system
(4) Class of range rate.

If any target report is missed the track will be coasted. Constant speed and acceleration (not constant velocity) is assumed during coast.

By class of range rate data is meant one of classifications A through D in which range rate data can ordinarily be placed. For a description of these classes see subsection 3.1 on page 11.

Additional target information from the sensor which can prove useful to the tracker is the bearing and range information from the search radar system. Ordinarily not used, such information can be useful for backup purposes.

So that the tracker can make some reasonableness checks, it should have the following information:

(1) limits on aircraft speed and
(2) limit on the ability of the aircraft to maneuver.

The limits on aircraft speed should include both upper and lower limits. For maneuver only an upper limit is appropriate. The maneuver limit is taken in the nominal tracker studied here as 522 ACP/scan (46° /scan). Use of this limit tends to result in a slower, but more consistent tracker than if no limit were placed on maneuver capability.

The automatic tracker assumed in this section and its subsections is a bimodal one. It functions either in its non-maneuvering or maneuvering mode depending on heading change as calculated using range rate differences, bearing differences, and target range.

The tracker is in its maneuvering mode if the scan to scan heading difference, calculated according to the expression in subsection 4.1 (page 17) is greater than or equal to 35 ACP (3°) per scan. Otherwise it is in its non-maneuvering mode.

In the non-maneuvering mode the tracker functions in the conventional manner as described in NAS-MD-321 and elsewhere. For present purposes a straightedge, data plot and protractor were used to determine headings in this mode.

In the maneuver mode the direction, but not the length of the velocity vector is changed according to the formula of the expression in subsection 4.1.

This change in direction can be either interim or final. If the change is based on a Class A or Class B range rate report, the shift in heading is considered to be final. If the datum is Class C the change is interim in nature and the next Class A or Class B datum is used for final correction. That is the change associated with the Class C datum is not included in the heading change calculation which is performed when a Class A or Class B datum becomes available.

If the report is Class D or if no datum is available the target is coasted. If the track is in the maneuver mode then the change in heading for a scan with no range rate data available is the same as that calculated for the previous scan. That is acceleration rather than velocity is assumed constant.

The track is also coasted if the scan to scan change in bearing is less than one ACP (0.09°). This is a non-trivial case for in the data base used in the test sample the following bearing sequence was reported: (see subsection 4.3.9 beginning on page 29).

Scan	Bearing (ACP)	Bearing Difference (ACP)
538	1747	-
539	1747	0
540	1746	-1
541	1750	4

Throughout this sequence the track was in the maneuver mode. The velocity vector is coasted of necessity through scan 539 for the calculation cannot be made with a bearing difference of zero. The velocity vector is also coasted through scan 540 because, in this case the average bearing difference, per scan, is less than one ACP.

The final calculation for heading change in this case is made at scan 541 when a good estimate of bearing difference (1 -1/3 ACP per scan) is available. The value of the bearing report at scan 540 is almost certainly too low by from 1 to 3 ACP.

4.3 Example of Use of Range Rate Data

The data base, consisting of target information from scans 289 through 616 is assumed to be used by the bimodel tracker described in subsection 4.2.2. This tracker, while functioning in its maneuver mode, calculates heading changes by making use of range rate data. The switch between modes is also determined from range rate data.

The following subsections provide essentially a line by line description of how the automatic tracker described in subsection 4.2.2 is expected to function with the data base. The general reader who is not interested in this level of detail may wish to skip to subsection 4.4 on page 33 where the results of this example of the use of range rate data are summarized.

4.3.1 Scans 289 through 311.

Initially the aircraft is reported on scan 289 after emerging from a blanked sector of airspace. The report on scan 289 has no range rate data corresponding to the 95 knot blind speed. It is therefore classified as questionable, Class C. The phase shift for the 78 knot blind speed is 208 , corresponding to a range rate of 45 knots, 124 knots, 202 knots, etc.

On scan 290 there is a beacon report and a strong search report. The search report is Class A, double precision, and the range rate is estimated as 53 knots. It is possible to calculate a minimum heading change of 1 ACP (0.1°) from this range rate and an assumed 45 knot rate at scan 289. Such a calculation is in the event correct, but in practice it would probably be of little value as there are only the two reports with which to establish the direction of the track. Nevertheless, be it noted that the two reports point to a direction of flight of 205° which is very close to the true direction of 202°. This true direction can only be inferred from reports not available at the time of scan 290.

At scan 293 the threshold for the maneuvering mode of the assumed tracker is reached with an apparent left maneuver of 4°.

The beacon report at scan 294 is incorrect as regards bearing information. It indicates a bearing from the radar of 1426 ACP (125.3°) whereas best estimate of bearing, known with certainty only after scan 295, is 1412 ACP (124.1°). In practice the bearing datum in beacon report 294 would be rejected as unreasonable since it indicates the impossible airspeed of 990 knots. At scan 294 the search report could be used. If it is so used, then a non-maneuvering track is correctly observed. At scan 295 following the range rate datum and the beacon position datum are both reliable and confirm that the aircraft is on a straight line (great circle) course. The plotted data indicate a slight left turn of 4°.

From scans 296 through 310 the beacon and range rate reports support each other and indicate an aircraft following a non-maneuvering trajectory. The mean heading change through these 15 scans is 2.7 ACP (0.23°) and the variance, from a mean of zero is 32 ACP^2. The range rate datum at scan 311 indicates a change in heading to the right of 16 ACP (1.4°). By the rules the nominal tracker will not adapt to this and the track will remain in its non maneuver mode.

4.3.2 Scans 312 through 330

At scans 312 and 313 the range rate data indicate a left turn of 8° extent. Careful measurement of the plot of the range bearing data indicates a turn of 10°. There is no beacon report at scan 315. Substitution of the range and bearing of the search report is acceptable. No maneuver is indicated. The reports at scan 318 and 320 are questionable (Class C).

The reports at scan 319 and 321 are of single precision (Class B).

The Class B single precision report at scan 321 suggests a maneuver of 4°. The plotted data confirm a maneuver of about 6°.

The reports at scan 323 and 325 are of single precision (Class B). No maneuver is suggested. At scan 327 a left turn begins. The duration of this turn is until scan 330. The data relevant to this turn are as follows:

Scan	Bearing ACP	Range 1/8 nmi	Range Rate Value (Knot)	Class	Heading Change (ACP)
326	1741	791	294.0	A	-1
327	1749	799	355.5	A	-101
328	1752	810	417.1	C	-284(interim)
329	1752	822	442.1	C	-467(interim)
330	1753	833	439.2	A	-850(final)

The heading change calculations at scan 328 and scan 329 are labeled interim because the range rate values are Class C. The final estimate of heading change is made at scan 330 for the three elapsed scans of 328, 329, and 330. The total heading change estimate of 951 ACP (84°) to the left badly overestimates the actual heading change. From plot data this change is estimated to be 512 ACP (45°). Presumably this discrepancy is due to the small difference in bearing which in turn enters the calculation for the nominal tracker as a denominator (subsection 4.1, page 17).

Curiously, use of search data does not change the results of the calculation as the values of the search bearing reports for scans 327 and 330 are the same as those of the beacon bearing reports.

4.3.3 Scans 331 through 340

During these scans the aircraft is moving directly away from the sensor on a heading of 1756 ACP (154°). The quality of the data is very high, even though one return, that at scan 332 is classified as Class C. Inspecting the rule for calculating heading change in the form $\Delta \dot{r}/r*\Delta\theta$, and realizing that $\Delta\theta$ is very small throughout this part of the flight, it is to be expected that the results would be erratic. In fact there are several instances in which $\Delta\dot{r} = \Delta\theta = 0$, so that the expression for change in heading becomes indeterminate. Nevertheless the assumed tracker has no difficulty with this portion of the flight as the change in range rate from scan to scan is very small (less than 3 knots).

The data from this portion of the flight were used to determine the expected deviation in the measurement of range rate. See subsection 3.2.1 (page 12).

4.3.4 Scans 341 through 369

This portion of the flight consists of three right turns of extent 42°, 40° and 52°. These turns are separated by two non-maneuvering legs, each of approximately 12 scans duration.

The maneuver beginning at scan 341 is estimated through scans 341-343 as extending through 588 ACP (52°). At scan 344 the search datum is of Class C quality as the return from both the 78 knot and 95 knot interrogations are of low precision. At the following scan, scan 345, the maneuver is properly determined to be completed. The overall estimate of turn of 52° through scan 343 is too high by 10°. As determined from plot data, the turn extends through 42°.

There is no search data at scan 347 and questionable data at scan 348. There is no beacon datum at scan 348.

At scan 349 the beacon datum is missing. It is only at scan 350 that the sensor receives a double precision search datum and a good beacon datum. At this scan one is able to confirm from these data that no maneuver has taken place since scan 346. Aircraft heading is measured from the range rate as changing 3° to the left during the seven scan period from scan 343 to scan 350, a negligible heading change.

At scans 351 and 352 the double precision data indicate no maneuvering. At scan 353 there begins a right hand turn. It is estimated that the aircraft has turned 65 ACP (6°) during this one scan.

The datum is Class C at scans 354 and 355, missing at scan 356 and Class B at scan 357. At scan 358 the datum is Class A and the turn appears to conclude at this scan. Total extent of the turn is calculated as 417 ACP (37°) using the range rate data. According to the plot data the best estimate of the extent is 455 ACP (40°).

From scans 358 through 366 the aircraft follows a straight line, as shown by both plot data and range rate data.

Beginning at scan 367 a right hand turn is made. The double precision range rate data and the beacon plot data are such that the turn is properly initated at scan 367 and terminated at scan 370. The extent of the turn is measured as 52° from the range rate data and this extent is confirmed by the plot data.

4.3.5 Scans 370 through 395

This portion of the flight begins with nine scans of a straight line portion of flight followed by a 45° turn. There follow nine more scans of straight line flight and a 90° right hand turn. See Figure 4-1.

The initial four scans (370-373) are properly supported with double precision range rate data. The quality of the datum associated with scan 374 is low on two counts: (1) there is no return associated with the 95 knot interrogation and (2) the bearing reported for the beacon return is apparently too high, indicating an unreasonable aircraft speed of about 700 knots. On scan 375 the datum supports a "no-maneuver" reading of the aircraft track.

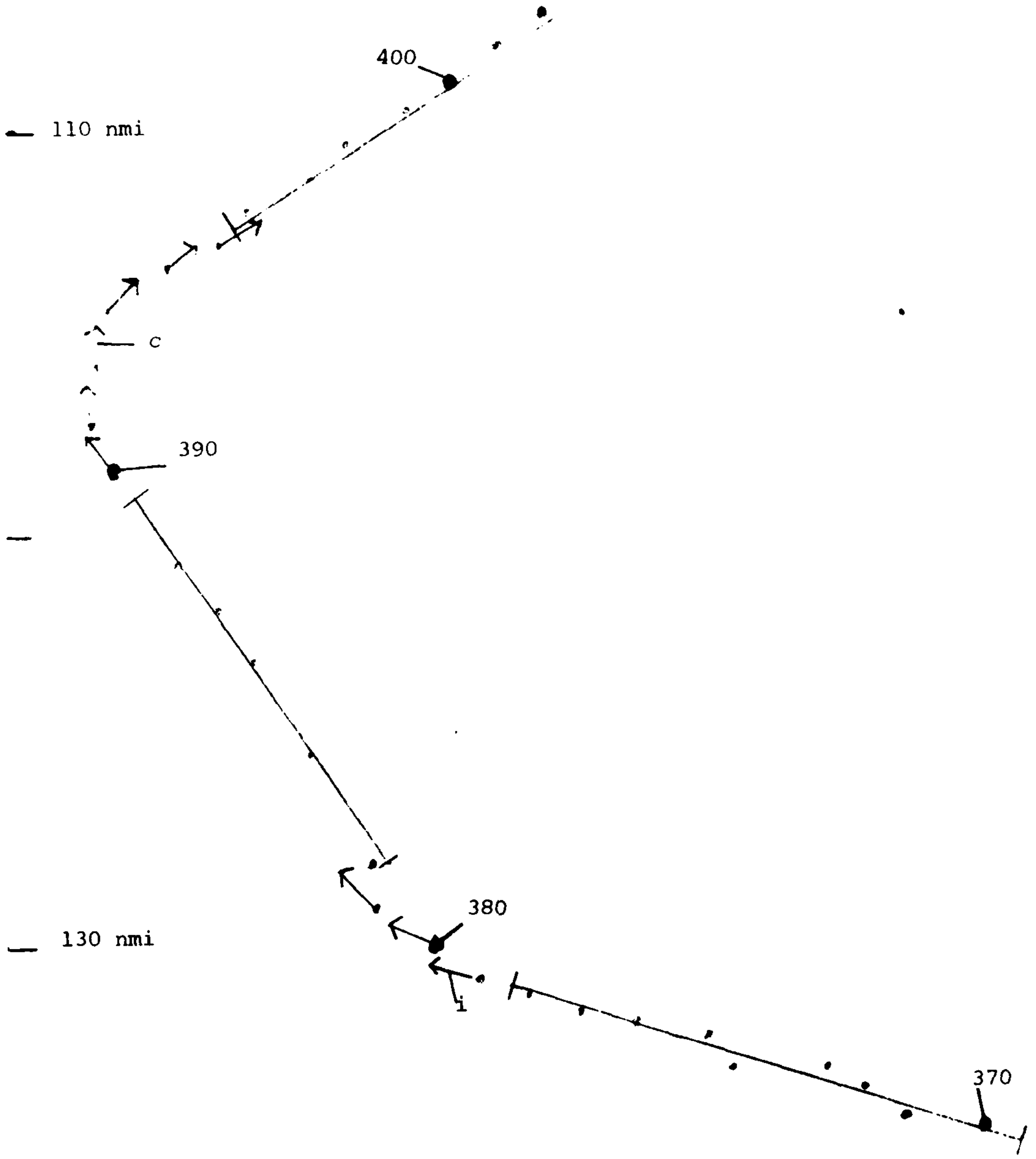


Figure 4-1. Illustrating the action of the nominal tracker from data collected during scans 370 through 402. The position of the beacon reports are plotted except for those at scans 383 and 385, which are missing. The nominal tracker is in the maneuver mode throughout scans 379-381 and 390-395. Elsewhere it is in the normal mode. The direction of the calculated velocity vector is plotted for these scans. "i" indicates interim computation and "c" indicates coast, as discussed in subsection 4.2.2 (page 20).

Scan 376 gives a normal non-maneuvering result. At scan 377 the datum suggests a false beginning of a left turn of about 6°. The supposed tracker rejects the beacon report of this datum. The report suggests a speed of only 190 knots, which may be considered unreasonably low for the B727 aircraft.

The datum of scan 378 is of high quality and indicates "no-maneuver."

The 37° right hand turn commencing at scan 379 and continuing through scan 381 is correctly observed by range rate processing. Its extent measured as 475 ACP (37°) from plot data.

From scans 382 through 385 some difficulty is encountered because of the quality of the data.

At scan 382 the search report is missing in its entirety. At scan 383 the search report is present but the beacon report is missing. At scan 384 the search report is again missing, beacon report present and at scan 385 the search report is again missing but the beacon report is present. Since there is no maneuver involved, it may be assumed that any tracker can function throughout these scans.

Any reasonable substitution of the beacon report position will result in a proper call of "non-maneuvering" for the target. Uncertainties can be resolved at scan 386 where the search report is of double precision. Combining it with the beacon report from scan 382 and the search report from scan 383, a heading change of 10 ACP (0.9°) for the scans from 381 to 386 is found. The nominal tracker will correctly indicate "no maneuver."

Scans 387, 388 and 389 have double precision search reports. These are consistent with a non-maneuvering target.

At scan 390 a 92° right turn commences with a heading change of 92 ACP (8°). It continues through scan 391 with an additional change of 169 ACP (15°). At scan 392 the bearing report is the same as at scan 391 so that the heading change cannot be calculated. The heading change is coasted in Figure 4-1. At scan 393 it is calculated as 59° since scan 391. At scan 394 the 95 knot report is missing so that range rate datum is unreliable (Class C). At scan 395 the turn is completed with an apparent additional change of heading of 17°. The total indicated extent of the turn according to the range rate data, is 99°. A careful estimate of the plot data indicates a turn of 92°.

4.3.6 Scans 396 through 420.

Throughout these scans the aircraft is essentially pursuing a straight course. The plot gives some evidence of a slight right turn of about 12° at scan 408.

The range rate data are of the double precision type through scan 401 and the accompanying beacon reports are such that the net heading change after six scans is 40 ACP (1.8°) to the left. No maneuver is indicated and the nominal tracker adjusts to this change only in its normal, non-maneuvering mode.

At scan 402 the search datum is missing and at scan 403 the beacon datum is missing. At scan 404 the net result of the three scans is that no heading change is indicated.

For the scans immediately following scan 404 there are Class A data only for scans 407 and 409.

The beacon datum at scan 407 will be rejected by the tracker because it corresponds to the unreasonable speed of 742 knots. The overall indicated heading change of 160 ACP (14°) will be indicated at scan 408. The observed heading change is about 137 ACP (12°).

From scan 408 through 421 the reports suggest, correctly, a non-maneuvering track. There are missing beacon reports at scan 412 and scan 414. The bearing estimate at scan 416 can provide trouble for an automatic tracker if it is not corrected. Since the indicated speed from scan 415 to 416 is an unreasonable 1278 knots, almost any tracker worthy of the name should be able to accomodate this difficulty.

4.3.7 Scans 421 through 430

This is a nominal 90° right hand turn.

Heading changes at scans 421 through 424 show a smooth right hand turn of duration 666 ACP (59°). There is no bearing change from scan 424 for the following three scans however, and there is no search report for scan 428 and no beacon report for scan 429. Finally at scan 430 there is a bearing change from scan 424 and the heading change can be calculated to be 341 ACP (30°). The total heading change for these scans, 421 through 430 is thus 89°, confirming the plotted heading change.

4.3.8 Scans 431 through 512

This is a very long part of the trajectory which includes six maneuvers, all consisting of right hand turns, of extent between 9° and 87°.

There is an initial maneuver at scans 435-436, which measures 31° from the plot data. Calculations using range rate data indicate a turn of 27°.

At scan 440 there occurs a slight maneuver estimated as 9 from plotted data and 14° from range rate data.

The five scans from 442 through 445 indicate a straight line path. At scan 446 the aircraft begins a right hand turn which ends at scan 452. From range rate data the extent of the turn is estimated to be 449 ACP (43°) and from plot data it is estimated to be 479 ACP (42°).

Beginning at scan 452 there is a comparatively long, turn-free path of seven scans.

At scan 459 begins a right hand turn which persists through scan 469. The data are poor from scans 463 through 467. Only at scan 468 is it possible finally to estimate the extent of the turn from range rate data. This estimate is 548 ACP (48°). From plot data best estimate is 546 ACP (48°).

From scans 470 through 473 the track follows a straight line. Then range rate data indicate a right hand turn commencing at scan 474. This turn is difficult to follow on the plot as it appears to start right and bend somewhat towards the left finishing up at scan 480 with a net right turn of 466 ACP (41°). The range rate data support this interpretation, including the right-then-slight left character of the turn. The range rate data indicate a net right turn of 426 ACP (37°).

The data of scans 481 through 484 indicate a straight part of the track and this indication is confirmed by plot data.

Commencing with scan 485 and extending through scan 490 the track makes a right hand turn. The plot data indicate an extent of 990 ACP (87°) for this turn and the range rate data indicate an extent of 873 ACP (77°).

Following scan 490 plot data and range rate data confirm that the aircraft continues on a straight line course through scan 512.

4.3.9 Scans 513 through 548

This part of the flight path consists of a very complicated S-turn. It is illustrated in Figure 4-2.

The turn starts with a heading adjustment of 3° right. This is followed by a left hand turn of 75° followed by a right hand turn of 222° and then a left hand turn of 37°. The total maneuver extends through 23 scans (4 minutes, 36 seconds) and the result is a net right hand maneuver of 117°.

The slight heading adjustment of 36 ACP (3°) right at scan 513 is confirmed by the plot data. A left hand turn commences at scan 515 and extends through scan 519.

The direction of the velocity vectors during the initial three scans

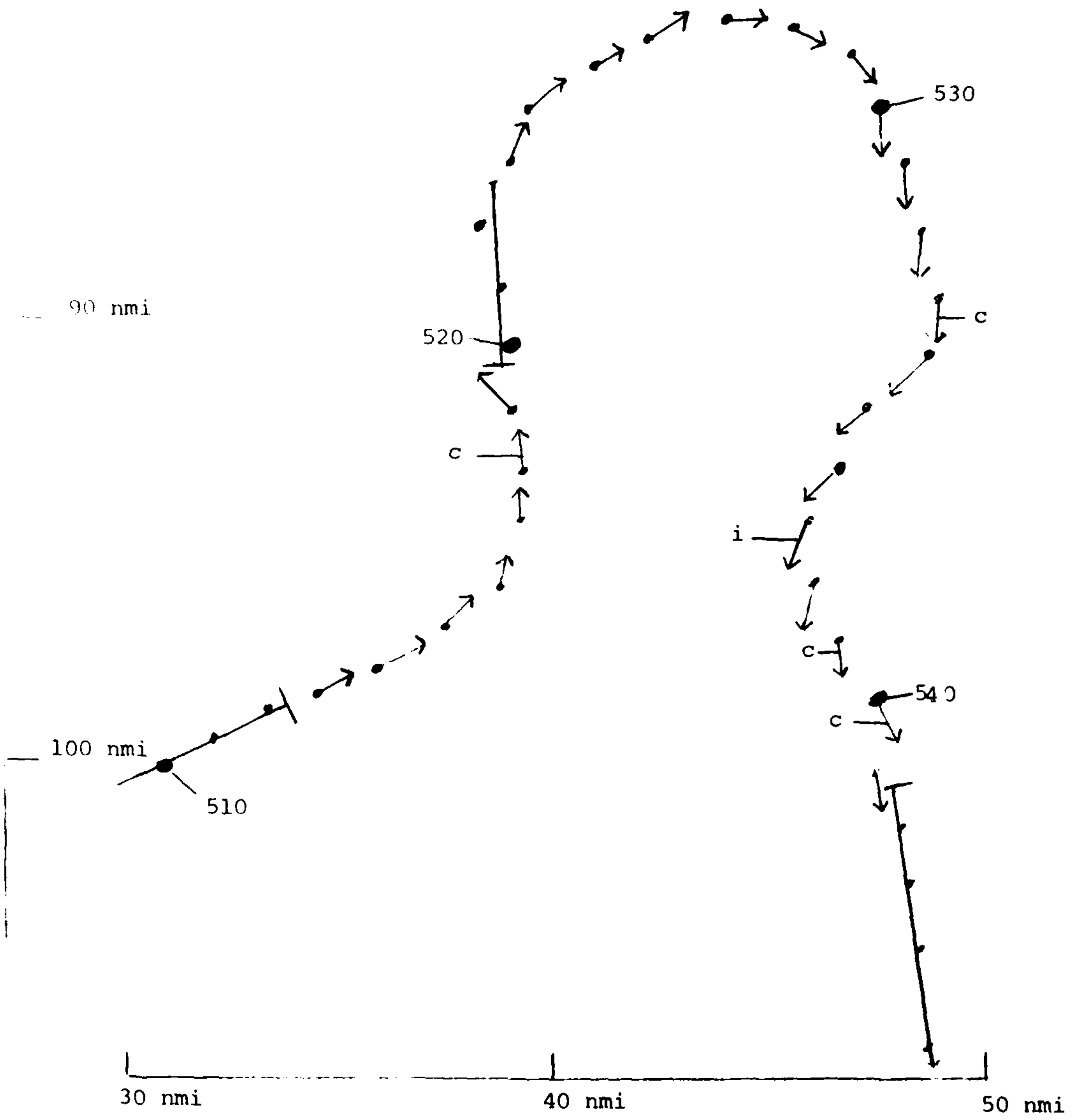


Figure 4-2. Illustrating the action of the nominal tracker for data collected during the S-turn. Beacon data is plotted for scans 510 through scan 544. The directions of the velocity vectors are illustrated when the tracker is in the maneuver mode. This occurs at scans 513 through 519 and from scans 523 through 541. "i" indicates interim computation and "c" indicates coast, as dicussed in subsection 4.2.2 (page 20).

4.3.10 Scans 549 through 598

This portion of the aircraft trajectory consists of a series of four right hand turns. It includes an erroneous call of a left turn, the only instance of such a call.

The right turn beginning at scan 548 and extending through scan 553 is measured, using range rate data, as 355 ACP (31°). Using plotted data it appears as 25°.

There is a missed search report at scan 557, a missed beacon report on the next scan 558 and a Class C range rate report at scan 559. There is no indication f a maneuver in the plotted data and none in the range rate data.

At scan 563 a right hand maneuver is started. This maneuver extends through scan 566 according to the range rate data. Range rate data indicate a turn of 53° and plotted data measure this turn as 50°.

At scan 573 there is a datum which is put into the Class D category. It occurs during the interrogation corresponding to the 95 knot blind speed. The response of this interrogation in each of the eight filters is as follows:

Filter	Power
0	1765
1	256
2	255
3	274
4	725
5	323
6	185
7	49

Following the usual rules (section 1), best estimate of the phase shift is determined by the response in filters 0 and 1 and the pulse to pulse phase shift appears to be 39°. Best estimate of actual phase shift is 84° from velocity information, but this estimate is not supported by the range rate data. The double peak of this distribution, with peaks in filter 0 and filter 4 is suggestive of two aircraft, corresponding to phase shifts of 39° and of 186°. It would be well if the radar could reject this kind of data out of hand. The phenomenon is probably rare enough. This is the only instance of this kind observed out of the approximately 650 returns which were examined.

Accepting the 39° shift at face value the nominal tracker indicates the beginning of a left turn at scan 573. This is immediately, but not entirely corrected at scan 574. The residual error is 3° left.

Beacon data are missing at scans 576 and 577. At scan 578 a right hand turn is indicated. Range rate data and plot data agree that the extent of the turn is 41°.

There follows a non-maneuvering portion of the flight from scan 579 through scan 588. The range rate datum at scan 582 is missing. No difficulty is involved.

Beginning at scan 589 and continuing through scan 593 a right turn is indicated. Range rate data indicate its extent as 33°, slightly greater than the plotted estimate of 30°.

From scan 594 through 598 the trajectory follows a non-maneuvering course as indicated by the range rate data and confirmed by the plotted data.

4.3.11 Scans 599 through 616.

This portion of the flight path begins with a maneuver towards the right of 93° following which the aircraft leaves the test area to the northeast. The maneuver is immediately detected by processing of range rate data. Its extent is estimated from range rate data as 56°. This is the poorest of the estimates of the maneuvers.

This comparitively poor result can be improved by making the tracker somewhat less responsive. It would appear however that such desensitization would, on balance, result in a generally poorer tracker.

4.4 Summary of Results Presented in Subsection 4.3

The test flight consists of a series of maneuvers of a B727 aircraft flying at a speed of approximately 430 knots at a distance of about 100 nmi from the MTD sensor. Between maneuvers the aircraft flies in a straight line. The maneuvers are detected by the processing of range rate data. The extent of the maneuvers is determined independently from a study of the plots of the position reports.

The flight is reported on a scan by scan basis with scans indexed from number 289 through number 616. The angle of bank is nominally 30 so that the nominal turn rate is 200 ACP per scan. Scan duration is twelve seconds.

Table 4-1 on the following page lists the observed maneuvers, their extent as estimated by integration of the heading change expression of subsection 4.1 (page 17) and their extent as measured from a plot of the range bearing data.

There are several features of tracking using range rate data which are worthy of remark.

Of the twenty-six entries in the Table, two refer to phantom turns, those indexed under scans 573 and 574. As explained in subsection 4.3.10 (page 31).

Table 4-1

Comparison of Estimate of Extent of Heading Changes

Scan Maneuver Starts	From Range Rate Data	From Plot Data
293	-4°	-4°
312	-8	-10
321	4	6
327	84	45
341	52	42
353	37	40
367	52	52
379	37	37
390	99	92
408	14	12
421	89	89
435	27	31
440	14	9
446	43	42
459	48	48
474	37	41
485	77	87
513	81	75
522	173	174
548	31	25
563	53	50
573	-11*	0
574	8*	0
578	41	41
589	33	30
599	56	93

* These maneuvers are induced by a range rate report corrupted by interference. See subsection 4.3.10 (page 31).

both these false turns are due to a common cause, an anamolous range rate report. Such a report could be suppressed by proper processing before its use in the automatic tracker. If not suppressed, however, it would appear to do little harm, as the net effect of the false report is an erroneous heading indication of 3° left, a relatively slight error.

There are four right angle turns in the Table. They commence at scans 390, 421, 485 and 599. There is not enough information to characterize the performance of range rate processing statistically for these maneuvers. Suffice it to note that of the four maneuvers range rate processing leads by 7°, is exact to within 1°, lags by 10° and lags rather badly, by 37°.

It is possible to modify the tracker, by requiring at least 2 ACP for bearing difference in the expression on page 17, that the lag for the 93° turn commencing at scan 599 is reduced from 37° to 14°. Such a modification, however, has serious consequences for the extended maneuver commencing at scan 522.

There are 10 maneuvers of 45° ± 10°. The root mean square heading error associated with them is 13°. Almost the whole of this quantity is associated with the overestimate of the maneuver commencing at scan 327.

The poorest results are obtained near the beginning and at the end of the run. The error is 39°, leading, for the 45° maneuver commencing at scan 327 and it is 37°, lagging, for the final right turn commencing at scan 599.

The best demonstration of the ability of range rate data to follow a maneuver is the long 173° maneuver beginning at scan 522. The nominal tracker follows it to within 1°.

In general the nominal tracker, working with range rate data, detects all turns immediately, that is within one scan of occurence, and is able to follow about 90% of them to within ten degrees of their final headings. This is believed to be far beyond the performance capability of trackers which use only position information.

Such tracker performance seems to require either roll angle or similar data linked down from the aircraft or, as has been shown, range rate data which can be available in the NAS en route system towards the end of this decade.

Further, the nominal tracker is indeed nominal. A tracker designed to use range rate data in the en route portion of the National Airspace System would be expected to give better results than those found here. Taking advantage of multiple coverage, one should be able to reduce the expected error significantly in cases where the angle between the velocity vector and the vector to the preferred sensor is small. One can process data from the secondary sensor for an improved estimate of heading change.

5. SUMMARY AND CONCLUSIONS

The next generation of long range search radars can have the capability of measuring directly a component of target velocity, the range rate. To determine how well this measurement could be made and if, once made, data from it could be operationally useful, a test flight of a B727 aircraft engaging in various maneuvers was observed by a prototype of this radar. The test flight took place generally at a distance of 100-130 nmi from the radar in a background free of ground clutter and precipitation response.

As a result of this test flight it was found that, at least in this case, range rate can be measured with a high degree of accuracy. It is a reasonable inference that range rate can be measured well for most, perhaps all targets of interest when conditions of radar background are good (no clutter, no precipitation). It may also be inferred that good measurements can be made when the radar background is poor.

A tracker which uses range rate data to determine the fact and the extent of an aircraft maneuver was prepared. Using the data gathered during the test flight this tracker was exercised to see how well it could detect and measure aircraft maneuvers expected in the en route portion of the National Airspace System.

Of the 24 maneuvers in the test all were detected in a timely manner, i.e. immediately upon start of maneuver. The maneuver was followed in all instances and the termination of the maneuver also noted. In many instances the extent of the maneuver was measured to within 5° of the extent determined from plot (range/bearing) data.

There are safety issues involved in maneuver detection. Early and accurate detection of aircraft maneuvers is useful if a conflict resolution system is not to be fooled into giving wrong, perhaps dangerous recommendations. The example given in figures 5-1 through 5-3 shows how conventional maneuver detection, such as that presently in use, may result in a potentially hazardous air situation.

Effort should proceed apace to demonstrate the usefulness of range rate processing as part of the tracking function. The purchase specification for the next generation of long range radars should include as an option the capability of processing phase data as described in Moving Target Detector -II Summary Report, FAA-RD-80-77. If the demonstration effort proves sucessful then the option should be exercised and range rate processing should be part of the en route tracker. The target data for initial deployment should be late 1988, when radars capable of generating range rate data can be initially commissioned.

By providing a greatly improved data base on which to prepare predictions of aircraft tracks, the use of range rate processing will support advanced conflict alert and conflict resolution algorithms and in doing so can provide an increased level of safety in the en route portion of the National Airspace System.

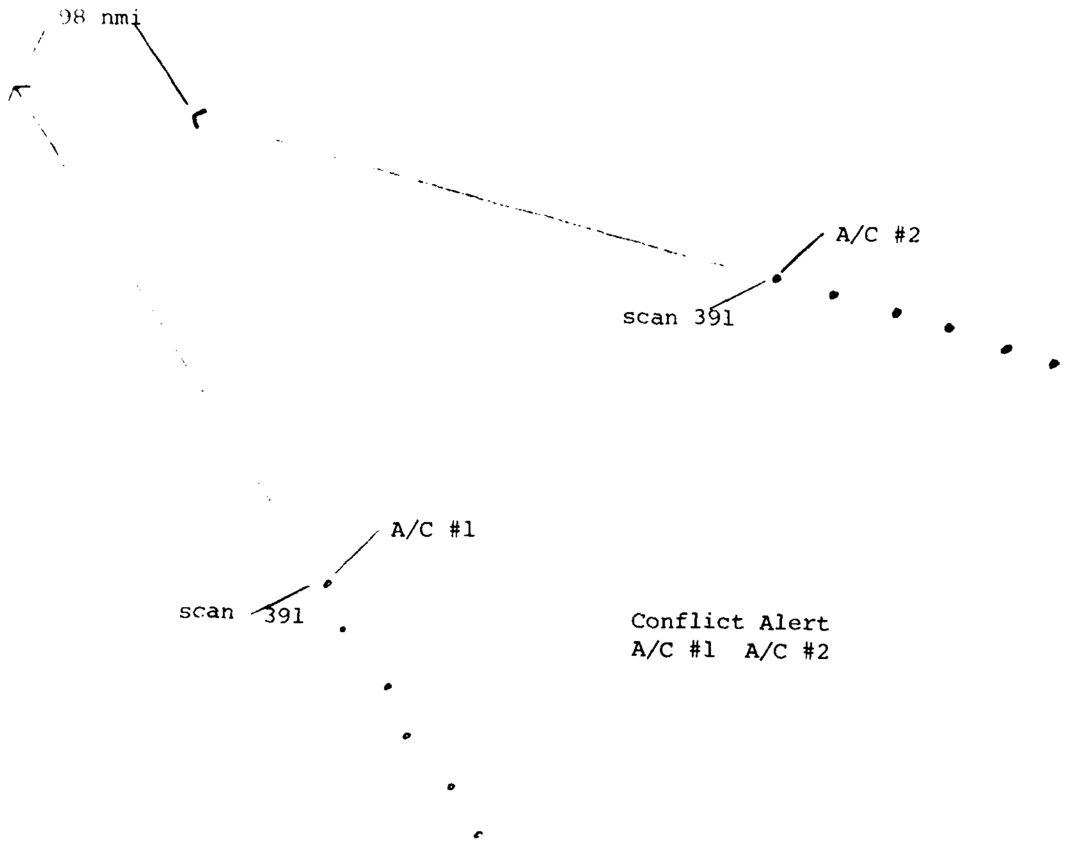


Figure 5-1. In this and in the following two figures there is presented an example of the importance of prompt detection of aircraft maneuvers. The reports associated with the test aircraft observed from scans 386 through 391 are plotted here and associated with an aircraft identified as A/C #1. Simultaneously A/C #2, with the same speed as A/C #1 is assumed to be cruising slightly North of West as shown. The Conflict Alert algorithm, part of the present operating software of the en route portion of the National Airspace System, is tripped at scan 391. It computes velocity vectors as shown by the arrows and as these are projected to yield a separation of 4.8 nmi at 2 minutes after scan 391 a conflict alert warning is issued at this scan.

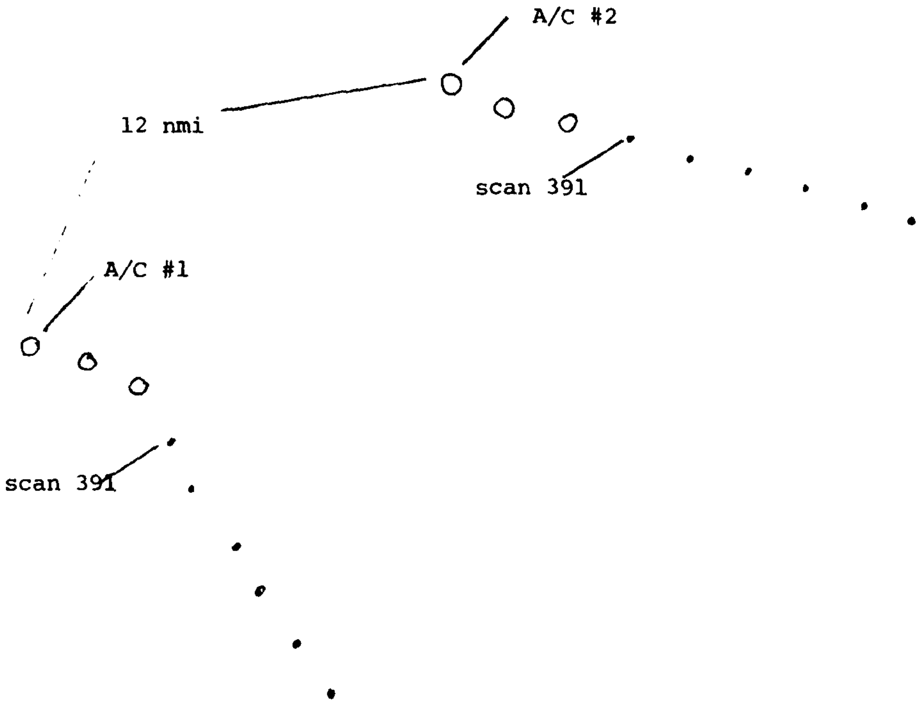


Figure 5-2. An automatic (or indeed manual) conflict resolution system may attempt to resolve the problem presented in the previous figure by issuing a left turn instruction to A/C #1. A reasonable estimate of the result of following such an instruction is illustrated here. After following the maneuver, the aircraft are expected to be on paralled courses with a comfortable separation of 12 nmi.

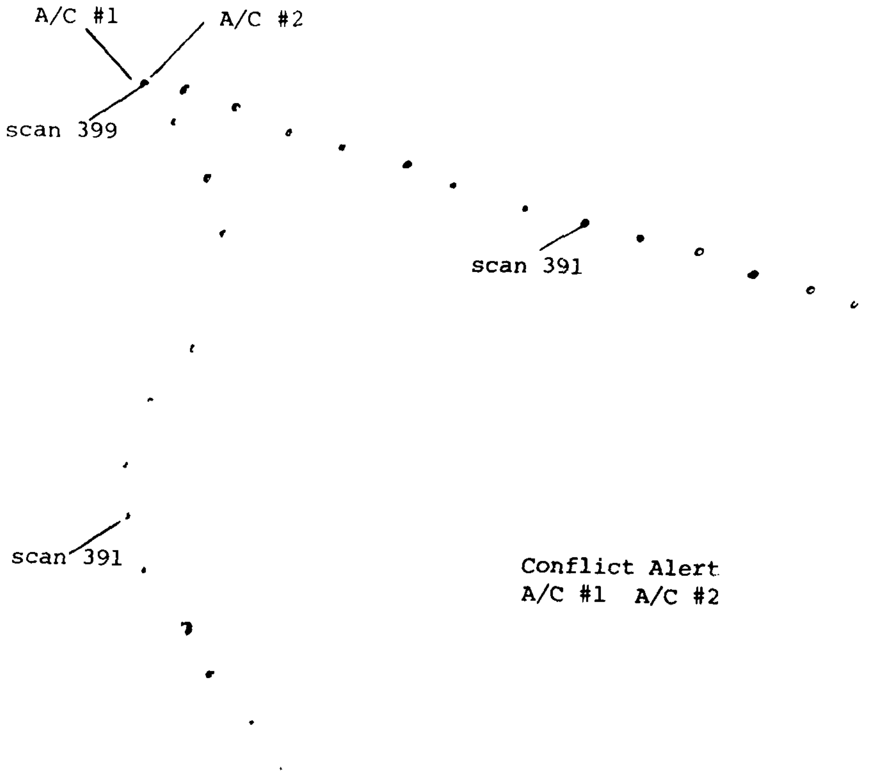


Figure 5-3. If, in the event shown in Figure 5-1, A/C #1 follows the left turn solution suggested in the previous figure then a very hazardous situation will develop. There is the potential for a midair collision eight scans (96 seconds) after the conflict alert warning at scan 391. As this example shows it can be vitally important that early information concerning aircraft maneuvers be available to any conflict resolution system, whether automatic or manual.

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