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Alex Kanaris, Petros Ioannou
University of Southern California

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by

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Field Test of Vehicle-Mounted, Forward Looking Range Sensor in Closed-Loop AVCS

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Abstract

The purpose of MOU-233 is to evaluate and test a low cost, short range radar sensor developed by Amerigon corporation through a subcontract with the University of Southern California. The radar is designed to be used as a ranging sensor for automatic vehicle following applications. It is intended to be mounted in the front of the vehicle and provide measurements of the distance between the front of the vehicle and the rear of any vehicle or object ahead within a maximum distance of 17 feet.

The output of the radar as supplied by Amerigon, is a 32-bit binary code, using one bit to represent each one of the range gates. In each sample, a bit value of '1' represents a range gate that detected a target and a value of '0' represents a range gate that has not detected a target. An algorithm has been developed to convert the binary code into distance measurements and to filter out undesirable effects such as noise, loss of target and other disturbances.

Two prototype radar units have been delivered to PATH by Amerigon and we used them on the PATH vehicles for testing and evaluation. In this report we present the results of the testing and the evaluation of the Amerigon radar.

Executive summary

The use of a radar as a ranging sensor for automatic vehicle following is not a new idea or a new application. Several companies and research institutes have already used radar, based on different principles of operation, as ranging sensors in automatic vehicle following applications. These radar, however, tend to be costly, which inhibits their wide-spread use in future passenger vehicles. They are also capable of measuring longer ranges since most of them are intended for applications such as intelligent cruise control.

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The Amerigon radar is developed to be a low cost radar and yet have an acceptable performance to make it suitable as a ranging sensor for close range automatic vehicle following. Therefore the radar could be suitable for advanced automatic vehicle following concepts such as platooning where the accuracy of short range measurements is more important. It could also be used as a redundant (secondary) ranging sensor to support a longer range sensor at short intervehicle ranges where safety becomes crucial.

The current study is divided into two parts. In the first part a prototype radar was calibrated and tested in the laboratory. In the second part the radar was mounted on a vehicle and tests have been performed while the vehicle was in motion. The output of the supplied prototype radar consists of unprocessed binary samples which are processed and filtered to provide a useful and accurate range indication. The processing and filtering algorithm was developed at the University of Southern California (USC).

In this report, we present the results of the calibration, field experiments and evaluation of the Amerigon radar sensor using the two prototype radar provided to PATH by Amerigon.

The main findings of the experiments and evaluation of the radar are as follows:
For tests in the laboratory, where the radar was stationary and the target was a moving aluminum foil pan, the radar met the performance specifications promised by the manufacturer for target distances of 9 feet to 17 feet when the relative motion velocity of the target was fairly greater than zero. When the velocity of motion of the target was close to zero, the radar failed to detect the target. In the vehicle following experiments performed at PATH, the test demonstrated that in a typical vehicle following situation the magnitude of the relative velocity is not sufficient for the radar to maintain a consistent and accurate detection of the relative position of the vehicle. The reason for this drawback is not due to hardware or software failures but on the Doppler principle on which the operation of this radar is based on.

The performance of the radar could be improved by increasing the low frequency response of the detection circuits in order to be able to detect targets at lower relative velocities. According to the manufacturer, accuracy of the target measurements at ranges smaller than 9 feet could be improved by fine tuning the gains of the respective gate range circuitry.

Despite its drawbacks, the low cost of this radar is a significant consideration and its performance must be viewed in this light. It may have great applicability as a low cost redundant sensor working together with a different type sensor such as FMCW, (which is not susceptible to losing a target at zero relative velocity), to increase the confidence in the readings of the primary sensor and to provide fail safe redundancy in case of malfunction of the primary sensor.

Keywords: Automatic Vehicle Following, Ranging sensors, Radar sensors, Automotive radar, Low cost radar.

Contents

1. Introduction

The purpose of this project is to evaluate and test a low cost, short range radar sensor developed by Amerigon corporation through a subcontract with the University of Southern California. The radar is designed to be used as a ranging sensor for automatic vehicle following applications. The radar is intended to be mounted in the front of the vehicle and is designed to provide measurements of the distance between the front of the vehicle and the rear of any vehicle or object ahead within a maximum distance of 17 feet at fixed time intervals of 4 msec. These range measurements could also be used to obtain an estimate of the closing rate of the vehicle with respect to the vehicle or obstacle ahead. The intervehicle spacing and relative speed measurements could be used by an on-board longitudinal control algorithm to calculate the inputs for the throttle and brake actuators in order to maintain a desired intervehicle spacing and guarantee no collision with any vehicle or obstacle in front. They could also be used to implement collision warnings or other intelligent vehicle applications.

The use of a radar as a ranging sensor for automatic vehicle following is not a new idea or a new application. Several companies and research institutes have already used radar, based on different principles of operation, as ranging sensors in automatic vehicle following applications. These radar, however, tend to be costly, which inhibits their wide-spread use in future passenger vehicles. They are also capable of measuring longer ranges since most of them are intended for applications such as intelligent cruise control. The Amerigon radar is developed to be a low cost radar and yet have an acceptable performance to make it suitable as a ranging sensor for close range automatic vehicle following. Therefore the radar could be suitable for advanced automatic vehicle following concepts such as platooning where the accuracy of short range measurements is more important. It could also be used as a redundant (secondary) ranging sensor to support a longer range sensor at short intervehicle ranges where safety becomes crucial.

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In this report, we present the results of the experiments and the evaluations of the Amerigon radar. The report is organized as follows: In section 2 we describe the main components and the principle of operation of the radar. The static range calibration and testing results are presented in section 3. In section 4 we present the decoding and filtering algorithm. The results of the experiments using the PATH vehicles are discussed in section 5 together with some recommendations. In section 6 we present the conclusions.

2. The apparatus and principle of operation

The Amerigon range sensor is a radar device based on reflected energy reception, commonly referred to as echo ranging. It uses a pulsed Continuous Wave (CW) approach referred to as "Integrated Domain Radar" (IDR). With this approach the cost constraints and the technical difficulties associated with microwave signal modulation, beam forming and sophisticated signal processing are avoided. The IDR radar can effectively detect targets at the short distance ranges needed for certain automotive applications such as blind spot detection, back-up aid, platooning etc., as long as the relative speed between the radar and the moving target is relatively high.

The Amerigon radar differentiates targets into 32 different ranges with an update rate of 250 readings per second. This rapid data rate makes tracking of fast moving targets practical. With a maximum range of about 17 feet, this sensor features a nominal ranging resolution of about 0.5 feet. The operation of this radar is described below, together with some general radar principles.

In general, the radar operation relies on two simple physical principles: In the first principle, the range (R) is calculated using the equation

$$R = t_d \frac{c}{2} \tag{1}$$

where t_d is the estimate of the round trip delay between transmission and reception of the transmitted signal and *c* is the speed of light in vacuum.

In the second principle, the relative velocity (the range rate) is calculated using the Doppler effect, as follows: A transmission at frequency f_0 reflected from a target moving with relative velocity u_r will be received as f_0+f_d. The change in frequency f_d, known as the Doppler shift, is given by the equation

$$f_d = f_o\left(\frac{c-u_r}{c+u_r}-1\right) = -\frac{2f_0u_r}{c}\left(1-\frac{u_r}{c}+\frac{u_r^2}{c^2}-\ldots\right) \approx -\frac{2f_0u_r}{c} = -\frac{2u_r}{\lambda} \tag{2}$$

where $\lambda=c/f_o$ is the wavelength of the transmitted electromagnetic signal.

The measurement of f_d is used to calculate the relative velocity u_r by the simple formula:

$$u_r \approx -\frac{f_d c}{2f_0} = -\frac{f_d \lambda}{2} \tag{3}$$

The IDR principle makes use of both of the above general principles and it is described using the simplified diagram of the radar architecture shown in Figure 1.

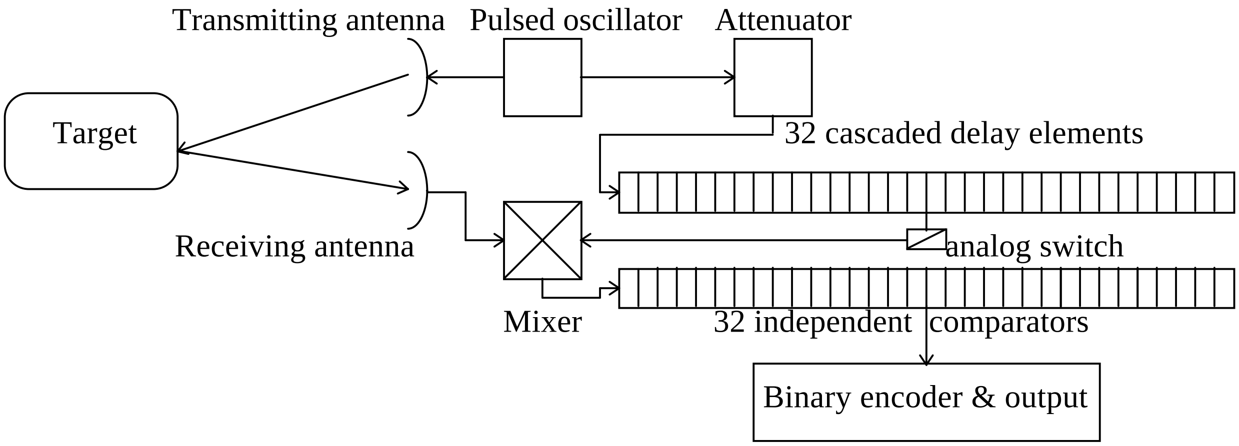

Figure 1: Simplified block diagram of the Amerigon radar and the IDR principle of operation.

The hardware components and architecture of the Amerigon radar are simple and inexpensive, benefiting from the popularity of cellular phone industry components. The transmitter consists of an oscillator and a transmitting antenna. The receiver consists of a receiving antenna, a preamplifier and mixer stage that mixes down to baseband, 32 cascaded delay elements to and the low frequency signal processing (LFSP) section. The LFSP part consists of 32 comparators and the encoder and output system. A microprocessor is used to handle the timing and the interfacing.

The oscillator generates a pulse train at a frequency of 5.8GHz with a pulse repetition rate of approximately 1 MHz. Thus, the waveform transmitted by the antenna is a wideband, non-coherent carrier.

The reflected signal, a delayed replica of the transmitted pulse train modified by the Doppler shift due to the motion of the target, is detected by the receiving antenna and feeds into the mixer. The mixer performs a multiplication of the received waveform with an attenuated and delayed signal from the oscillator that yields a signal at frequency equal to the Doppler shift f_d. The pulses from the oscillator feed into a delay chain consisting of 32 cascaded delay elements. Each element in the cascade adds a delay of 1 nanosecond. The 32 comparators sample the output of the mixer in the audible frequency range. We believe that equivalent time sampling is being used to simplify the analog switching requirements. In effect, the signal received at the receiving antenna is being compared to the signal from each delay element. Therefore, the serial number of the comparator that detects a waveform coincidence signifies the amount of delay that the radio frequency pulse incurred in propagating to the target and back. We obtain 32 binary decisions from each of the 32 comparators (“range gates”). This string of 1s and 0s forms a 32 bit binary code which is output serially through an RS-232 port to the host computer.

The RS-232 serial interface operates at a speed of 57600 bits/sec and supports up to four radar units. The command from the host computer to the interface to start transmitting data samples is:

```
> LD\r\n
```

In response to this code, the interface starts transmitting messages at a rate of 250 messages per second, each message consisting of:

```
< 0xAA, long radar 1, long radar 2, long radar 3, long radar 4
```

The command from the host computer to the interface to start transmitting data samples containing radar unit #1 only is:

```
> L1\r\n
```

In response to this code, the interface starts transmitting messages at a rate of 250 messages per second, each message consisting of:

```
< 0xAA, long radar 1
```

The command from the host computer to the interface to stop sending is:

```
> \xB1\r\n
```

which is the ‘Escape’ key code.

The binary coded messages received from the interface must be decoded and interpreted by an algorithm in the host computer to deduce the time of flight t_d, i.e. the time for the signal to reach the target and come back. The time of flight data are passed through a filter developed by USC in order to reduce the effects of noise and the tendency of the radar to miss the target when the relative velocity is small or zero. The filtering algorithm also incorporates equation 1 that is used to calculate the range from knowledge of t_d. The algorithm is described in detail in section 4. The output of the filter is the estimate of the target range.

The main drawback of the principle on which the Amerigon radar is based is the fact that for relative speeds of zero or near zero the Doppler shift is zero or very close to zero which makes detection of the target not possible.

3. Static Range Calibration and Testing:

3.1 Calibration

The Amerigon radar is a sensor whose raw data output consists of a range gate number that classifies the target as being present at one or more out of 32 possible ranges. The correspondence of the range gate number to a specific distance was unknown and has to be found via calibration. Calibration was performed by obtaining a number of measurements at known target distances and fitting them to the radar output set. The developed mapping between the range gate number data and distance was used in all subsequent tests.

The calibration tests were performed as follows: A prototype radar was mounted on a vehicle at the Amerigon corporation laboratory. The test target was an aluminum foil pan obtained from the supermarket, approximately 8 by 11 inches at the bottom, with 2 inch walls. The target was placed at a selected distance from the antenna and was shaken manually in order to create relative speed and be detected by the radar.

At each selected position the target was oscillated with a small amplitude at different speeds. When the speed of oscillation was fast we were able to obtain a consistent reading. When the speed was zero, the radar could not detect the presence of the target. This response was expected due to the principle of operation i.e. the Doppler effect. When we increased the speed of oscillation of the target slightly, the target remained invisible to the radar until a certain point that the speed of oscillation was sufficient for a consistent detection. Increasing the speed of oscillation further the output of the radar changed to another consistent reading. In almost all the tests two consistent readings could be obtained, one corresponding to slow target velocity and another corresponding to fast target velocity. We refer to the reading obtained with a fast moving target as the “fast target” reading and the reading obtained with a slow moving target as the “slow target” reading. Since the readings from the fast target are expected to be more reliable these data points were used for calibration.

Figure 2 shows the correspondence of the gate numbers and the target range. The mapping is linear as implied by the principle of operation, especially at distances beyond 9 feet, with almost no discrepancy. It is clear from figure 2 that there is a discrepancy at short ranges, between 1 and 9 feet. This discrepancy is an indication of some anomaly in the response of the radar tested. According to the Amerigon engineers, this problem can be alleviated by fine tuning the gain of the comparator circuits dedicated to these ranges.

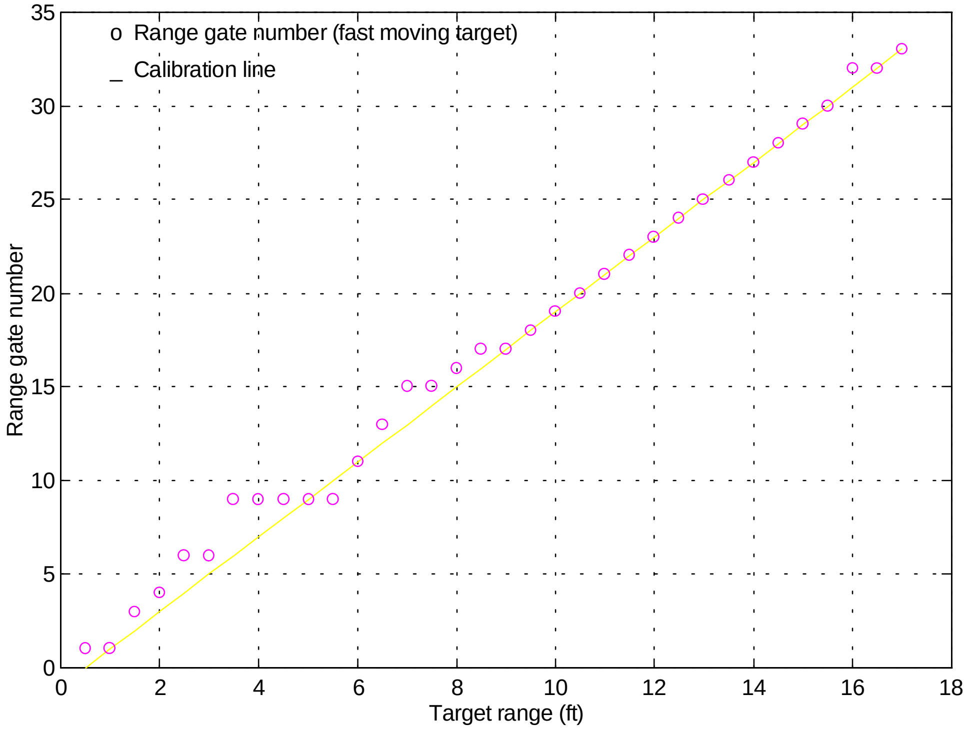

Figure 2: Radar range calibration

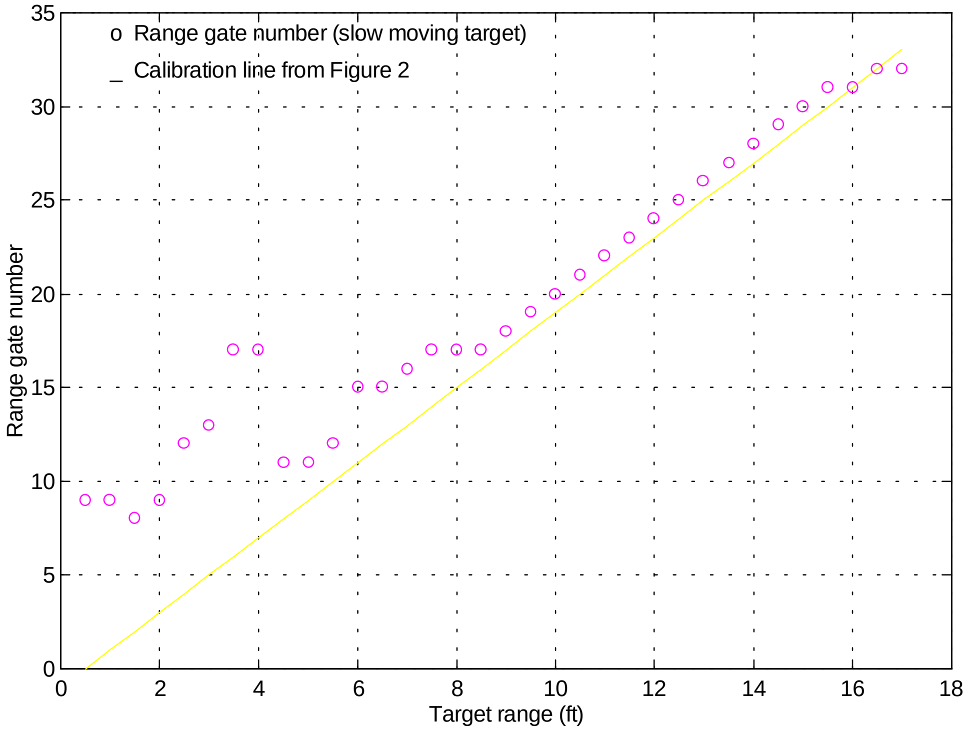

Figure 3: Effect of slow moving target measurements on calibration

The slope of the linear mapping was chosen by using the more consistent data obtained at distances of 9 feet and above.

In order to examine the effect of the "slow moving" target, i.e., small relative target speed, on the calibration line obtained in figure 2 based on the "fast moving" target data, we plot the range gate number for the "slow moving" target versus the actual target range together with the calibration line from figure 2. The results are shown in figure 3. It is clear that for target ranges lower than 8 feet the discrepancy is significant and the readings could be considered erroneous. At ranges greater than 8 feet the readings are reasonably accurate, even though they are less accurate than the corresponding readings shown in figure 2.

3.2 Static Tests

The same set-up used for calibration was also used to perform further tests. The calibration line obtained in Figure 2 is used to map the gate number data into a range. Table 1 shows the results of tests where the target was on the same axis as the primary beam of the antenna. Data for "fast moving" and "slow moving" targets are recorded and the estimated range and corresponding error were calculated as shown in table 1. For target distances of 9 feet and above the accuracy is excellent. The error increases at close ranges. With "slow moving" targets, there is some discrepancy at all distances, due to the low relative velocity of the target.

Amerigon radar accuracy tests (on-axis)						
	Fast moving target			Slow moving target		
Actual Range (ft)	Gate number	Estimated range (ft)	Error (ft)	Gate number	Estimated range (ft)	Error (ft)
0.5	1	1	0.5	9	5	4.5
1	1	1	0	9	5	4
1.5	3	2	0.5	8	4.5	3.5
2	4	2.5	0.5	9	5	3
2.5	6	3.5	1	12	6.5	4
3	6	3.5	0.5	13	7	4
3.5	9	5	1.5	17	9	5.5
4	9	5	1	17	9	5
4.5	9	5	0.5	11	6	1.5
5	9	5	0	11	6	1
5.5	9	5	-0.5	12	6.5	1
6	11	6	0	15	8	2
6.5	13	7	0.5	15	8	1.5
7	15	8	1	16	8.5	1.5
7.5	15	8	0.5	17	9	1.5
8	16	8.5	0.5	17	9	1
8.5	17	9	0.5	17	9	0.5
9	17	9	0	18	9.5	0.5
9.5	18	9.5	0	19	10	0.5
10	19	10	0	20	10.5	0.5
10.5	20	10.5	0	21	11	0.5
11	21	11	0	22	11.5	0.5
11.5	22	11.5	0	23	12	0.5
12	23	12	0	24	12.5	0.5
12.5	24	12.5	0	25	13	0.5
13	25	13	0	26	13.5	0.5
13.5	26	13.5	0	27	14	0.5
14	27	14	0	28	14.5	0.5
14.5	28	14.5	0	29	15	0.5
15	29	15	0	30	15.5	0.5
15.5	30	15.5	0	31	16	0.5
16	32	16.5	0.5	31	16	0
16.5	32	16.5	0	32	16.5	0
17		17	0	32	16.5	-0.5

Table 1. The range measurement accuracy of the Amerigon radar.

When the target is not on the maximum response axis of either the transmitting or the receiving antenna beam (or both) we have a signal loss which we refer to as the "Deviation loss". For any antenna, the deviation loss varies from zero decibels (0 dB) on the maximum response axis to several decibels off the axis. The radiation pattern of the Amerigon radar antenna has been designed and tuned in a microwave test lab, specifically for the vehicle following application.

We evaluated the radiation pattern of the antenna with the radar mounted on a vehicle at the Amerigon corporation laboratory. The off-axis response and the coverage of the radar was evaluated by placing and manually oscillating a piece of aluminum foil target (the same as in the other tests) at different positions and recording the corresponding readings from the radar. To determine the limits of the off-axis response, we repeatedly moved the target along a horizontal line from an off center position towards the center and recorded the position (on a two dimensional map) where the target was detected for the first time. This experiment was repeated many times, at five different distances, on each side (i.e. from the left and from the right). The results are shown in figure 4. It was found that the radar could not detect a target which was more than 2.5 feet off-axis. The sensitivity of the side lobes of the antenna was so low that the small aluminum target could not be detected reliably at any point beyond the boundary defined by the points shown in figure 4.

The estimated range for an off-axis target as depicted by the diagram in figure 4. The little circles represent the position of the target, and the column on the right represents the corresponding readings from the radar. We can see that there was always an error of about a foot, even after trigonometrically calculating the exact distance from the radar to the off-axis target. Figure 5 shows the radar calibration line, the off-axis target readings to the left and to the right of the antenna, and the corresponding on-axis readings for comparison purposes. The figure indicates that there is a slight asymmetry in the off-axis response.

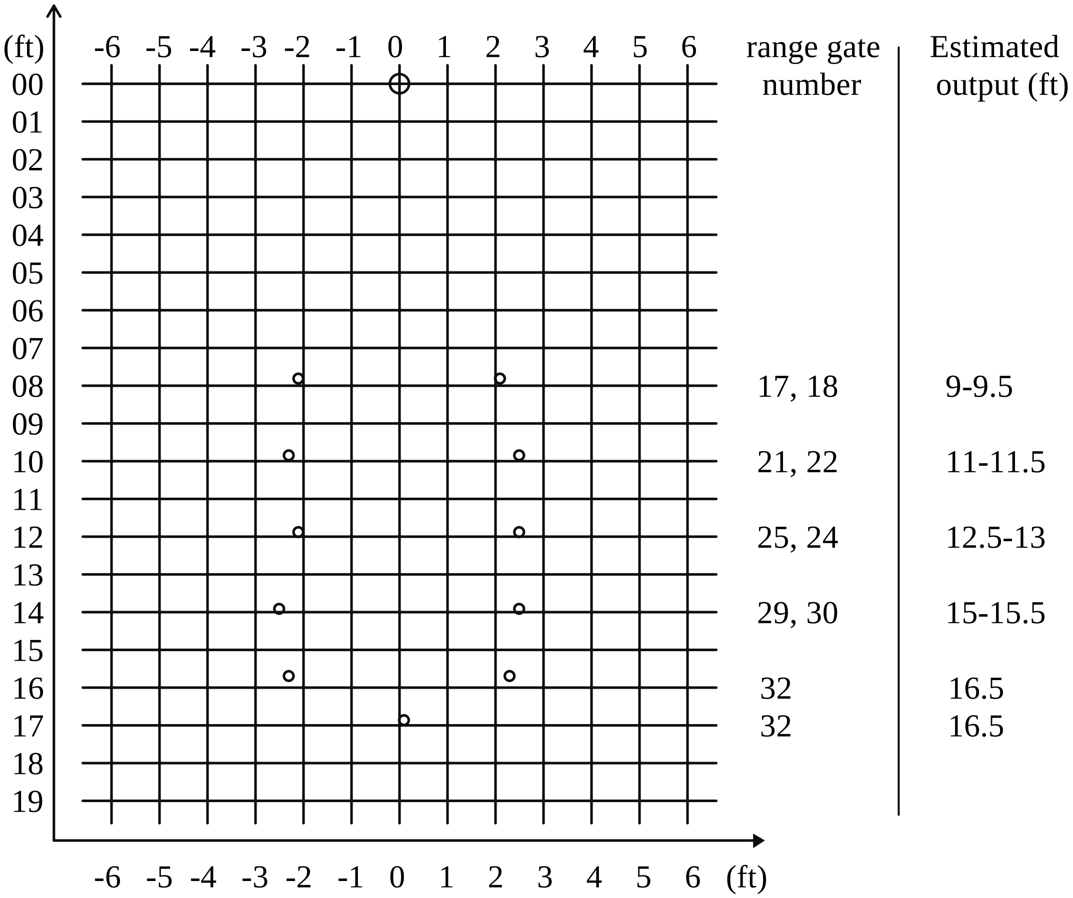

Figure 4. The radiation pattern of the Amerigon radar.
O: the position of the radar
o: the position of the target

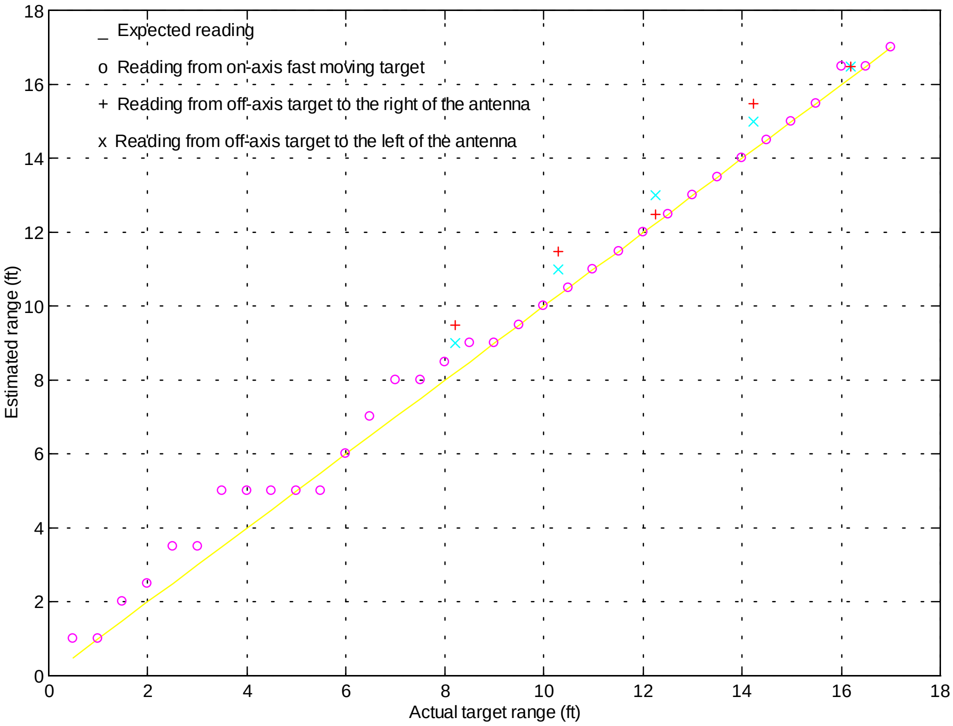

Figure 5: Off-axis response versus on-axis response.

3.3 Temperature variation tests

In the process of the radar evaluations it was found that the accuracy of the measurements was somewhat sensitive to temperature. Amerigon tested their radar by placing it in a controlled temperature chamber until its temperature stabilized at some selected level, then took it out and tested it immediately. They have provided test data for two radar samples for the temperature range -20°C to +85°C. The results are listed in Table 2. The radars were tested by moving a target back and forth at different distances from the antenna until a specific range indication was obtained. This range number was used to obtain the estimated range distance using the calibration line of figure 2. The estimated range was compared with the actual range of the target which was also recorded. The results, shown in table 2, demonstrate a dependency of the measurements on the temperature. This dependency appears to be higher at lower ranges which is misleading because, as demonstrated with the static tests, at short ranges the radar readings could have considerable errors. In practical use, the temperature of the radar unit is relatively stable (actually it gets rather warm due to the power dissipation of the electronic components inside) therefore the temperature effect can be thought as just another factor affecting the static calibration of the unit. Based on this assumption (that the temperature is not varying much during the operation of the unit) we have not attempted to compensate the results for temperature variations.

RADAR SENSOR TEMPERATURE SENSITIVITY EVALUATION										
			-27 C.			**19 C.**			**85 C.**	
Radar Gate Number	Estimated range		L.T. position	S.T. position		L.T. position	S.T. position		L.T. position	S.T. position
(unit #1)	(ft)		(ft)	(ft)		(ft)	(ft)		(ft)	(ft)
#8	5		3.67	3.40		4.46	3.83		4.27	4.17
#16	9		7.75	7		9.02	7.65		8.52	8.19
#24	13		11.35	10.75		12.62	11.54		12.85	12.27
#32	17		17.19	14.69		16.10	15.83		17.12	16.71
(unit #2)										
#8	5		3.79	3.60		5.23	4.33		4.60	4.23
#16	9		9.48	7.5		10.58	8.33		8.58	8.10
#24	13		13.33	11.40		14.81	12.48		12.98	12.33
#32	17		18.02	15.62		18.42	16.25		17.04	16

L.T.: Large Target (a 12x12 inch flat piece of sheet metal)
S.T.: Small Target (a 4x4 inch flat piece of sheet metal)

Table 2: Radar Sensor Temperature Sensitivity Evaluation.

4. The filtering algorithm

The Amerigon radar has been found to report the relative distance rather erratically which is a natural consequence of the fact that it is a Doppler based sensor whose output tends to vanish when the relative velocity to the target is zero or near zero. This leads to a fundamental inherent limitation in its applicability for vehicle following environment where it is expected that the relative velocity between vehicles is close to zero most of the time.

Preliminary tests of the Amerigon radar had also revealed that it is subject to frequent failures in reporting the relative distance when the relative velocity is near zero, where the error is always on the positive side, i.e. the target appears further away than it really is. It is also subject to infrequent noise spikes with consequential erroneous reporting of the relative distance where the error is on the negative side, i.e. the target appears closer than it really is.

The nature and frequency of occurrence of the errors were used to design a particular filter design that tries to compensate as much as possible for the "idiosyncrasies" of the Amerigon radar sensor.

The objectives of the filter, can be summarized as follows:

The radar data filter shall reduce the frequency of erroneous data samples and reduce the magnitude of the errors. The filter shall not introduce excessive delay in the processing of the data samples. The filter shall discriminate and prioritize the processing of the data according to the perceived behavior of the target. A target perceived as approaching the radar antenna shall receive the highest priority, corresponding to the potential threat of imminent collision. A target perceived as receding from the radar antenna shall receive regular priority, corresponding to the likely scenario of a vehicle accelerating away. A target perceived as stationary in relation to the radar antenna shall receive low priority, corresponding to the likely scenario of a vehicle being followed at an almost constant relative distance with near zero relative velocity. Finally, and most important, when one or more targets appear at multiple distance readings relative to the radar antenna, the samples that represent the nearest target will be given greater weight than the samples that represent further away targets.

Based on these requirements and especially the last one, we needed a non-linear type of filter in order to satisfy all of them. Therefore, an "envelope" type filter was selected to implement the real time processing of the radar data. When the data samples represent one or more targets at multiple distances, the filter will attempt to outline the envelope that encloses all data points. This outline curve represents the "most threatening" target.

The envelope filter is traditionally characterized by four discrete slopes, corresponding to four discrete time constants and therefore it is described in terms of these time constants. These represent the "Attack", "Sustain", "Decay" and "Release" parts of the curve, also known as ASDR, as seen in figure 6.

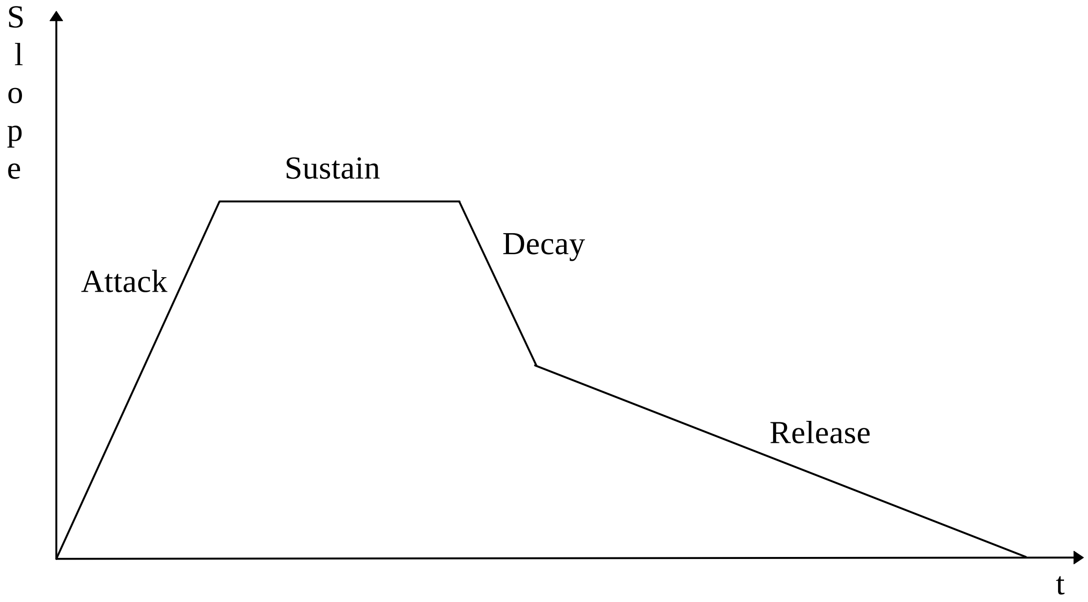

Figure 6. The ASDR “envelope” type filter.

In our filter implementation, we have implemented a state machine, (Finite State Machine, FSM for short), inspired by the ‘envelope’ filter. In general, an FSM can be represented by a state table which has a row corresponding to every internal state of the machine and a column corresponding to every input symbol (sometimes called input state). The entry in row q_i, column I_j represents the next state and the output produced if I_j is applied when the machine is in state q_i. This entry is denoted by $N(q_i, I_j)$, $Z(q_i, I_j)$, where N and Z are called the 'next state' and 'output functions' respectively of the machine. This type of sequential state machine whose output is a function of both the input and the present state is called a Mealy machine [1].

Mathematically, a Mealy machine is often represented by a quintuple (I, O, Q, N, Z), where I is the input alphabet, O is the output alphabet, Q is the set of states, N is a mapping from $I \times Q$ into Q and Z is a mapping from $I \times Q$ into Z. The operation of the machine is as follows: Let the machine initially be in some state $q_i \in Q$. If it receives an input $I_m \in I$, it produces an output $z_k \in O$ and goes to state $q_j \in Q$ at the next instant of time. The next state q_j and the output z_k are uniquely determined by the present state and input [2].

The state table representation and/or the state diagram (state transition graph) representation are more convenient and most frequently used. The state table or the state diagram of a Finite State sequential Machine can be used to determine the output sequence generated by any input sequence for any initial state.

We have chosen four discrete states and four events that trigger the switch-over from one state of the envelope filter to another. Due to the similarity with the envelope filter, we have named the states of the filter "Attack", "Sustain", "Decay" and "Masking". The nature of the data samples does not call for a "Release" state, therefore we called the fourth state the "Masking" state.

During the "Attack" state, the rate of change of the range output from the radar is limited to be less than 122 ft/sec (83.2 mph). Such high relative speeds are considered to be unrealistic for the applications the radar will be used for. Therefore radar readings that correspond to relative velocities higher this level are considered to be due to noise and are filtered out.

The "Sustain" state represents the scenario that a target is seen by the radar at the same range during two consecutive samples. This scenario is likely to indicate an upcoming reduction in relative velocity with a resulting loss of the target in the subsequent samples. It may be also due to a quantization error since all readings are quantized to 5 bits of resolution. The "Sustain" stage of the filter attempts to mask the fact that targets at zero relative velocity cannot be detected with a Doppler radar, by stretching the last reliable detection for as long as we think is reasonably possible. Therefore, we have chosen a very long time constant, and we set the slope of the "Sustain" filter stage at 3 bits/sec, corresponding to a target receding rate of 1.5 feet/sec. (1.02 mph). In other words, if two consecutive readings point to the same range gate number, any subsequent readings are modified to correspond to a maximum rate of change of range of 1.02 mph.

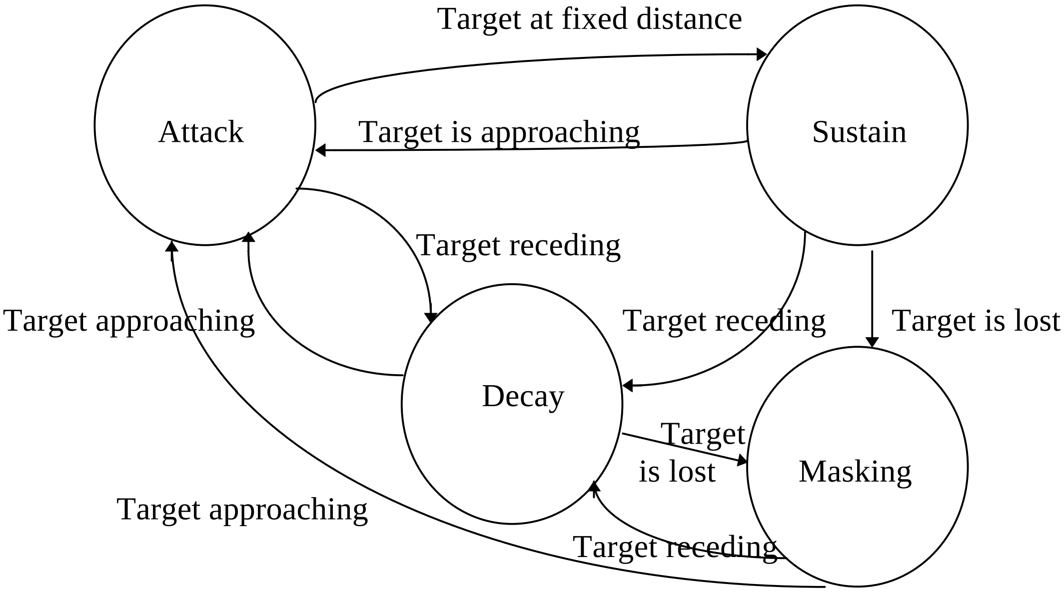

Figure 7: The FSM representation of the filter.

The "Decay" stage of the filter takes care of the situation where the target is moving away from the radar. Since the speed of the possible targets (which are considered to be passenger vehicles) cannot be changed instantaneously or faster than a certain rate, the radar readings could be modified to correspond to speed changes that are within the practical limits.

We set the slope of the "Decay" filter stage such that the radar range output tracks the typical range and velocity of a leading vehicle accelerating away after a period of constant intervehicle distance as seen in out data set and also as predicted by a simplistic "limited acceleration" model. This must be seen with the understanding that these tests were not attempting to represent extreme cases. We simply assumed that an acceleration of 0.3g might be applied at the leading vehicle while the radar output data is being "masked". We assumed that the masking period is equal to the "Sustain" period. Through an iterative process we determined this period to be approximately 0.35 seconds. Therefore, with an acceleration of 0.3g, a relative velocity of up to 1.03 m/sec may develop while the data is being masked. (Unit conversions: 1.03 m/sec = 3.38 feet/sec = 2.30 mph). Therefore the "Decay" stage filter has to be able to match that relative velocity. We set the slope of the "Decay" filter stage equal to 7 bits/sec, corresponding to a target receding rate of 3.5 feet/sec, equal to 2.4 mph. The rough estimate based on predicted acceleration was validated as this particular value of filter slope seems to minimize the range error of the Amerigon radar for the particular data sets that we have in our hands. Certainly, we cannot prove and we cannot even say that it is optimal in a general sense.

The “Masking” state is entered when the radar loses sight of the target. It represents the assumption that a target is likely to be at a fixed distance from the radar and the relative velocity of the target is very close to zero. From the point of view of the AVCS designer this time constant to be chosen for the masking state is a critical one. Every time the intervehicle distance (i.e. the distance to the target) tends to stabilize, the radar tends to lose sight of the target. We may set the slope of the “Masking” filter stage to zero, in effect holding the last detected position of the target constant until some relative velocity disturbance causes an update. Alternatively, we may chose the slope to be non-zero, so that the filtered output of the radar will emulate a target moving away at a fixed velocity. For example, the "Masking" state can be considered as an extension of the "Sustain" state and it may employ the same time constant.

If we choose a non-zero slope to implement the “Masking” state, every time the radar loses sight of the target the throttle controller will attempt to accelerate towards the target until it reaches a relative velocity equal to the apparent departure velocity of the target. It should be noted that the choice of the slope for the "Masking" filter stage can determine if the controller will have a tendency to lose the target frequently or if the effect of the filter will result in a "busy" and somewhat "aggressive" ride for the passengers in the following vehicle. Therefore we can trade-off ride quality at the expense of larger spacing errors "on paper". It seems that some "tweaking" and some "manual fine tuning" of this parameter would be called for if we were to attempt the implementation of an AVCS system that uses the Amerigon radar as the only source of range data for control purposes.

5. Field tests at PATH

5.1 Experimental set up

We tested the Amerigon radar at the Richmond Field - PATH headquarters. We mounted the radar and antenna on a wooden platform on the front of the vehicle. On the same wooden platform we had another instrument whose function is basically the electronic equivalent of a measuring tape. It is made by a company named "Rayelco". It measures the length of a wire that is extended from the front of the following vehicle and attached to the rear of the leading vehicle. The “Rayelco” instrument is used to obtain an accurate independent reading of the intervehicle spacing.

The "Rayelco" instrument wire was attached to the rear of the leading vehicle, near the license plate. Then both the leading vehicle and the following vehicle were driven manually on the streets inside the Richmond Field campus, which is not open to vehicular traffic. Therefore all tests were done without any interfering presence of other vehicles. The drivers of the vehicles were in contact via a wireless radio voice link. The driver of the leading vehicle was instructed to accelerate to a certain speed, typically in the 35 mph to 50 mph range and then try to maintain that speed until the completion of each test. The driver of the following vehicle was trying to follow the leading vehicle and at the same time maintain a desired intervehicle distance. Of course, due to limitations in the driver's judgment of distance and reaction time, this was not always achieved. But this "imperfection" was not a problem in any way since it automatically provides us with sample points at a wide variety of relative distances and relative speed levels.

Eight different runs were performed. Each run contained two sets of measurements, one from the Amerigon radar and one from the reference instrument. The results are plotted in the figures A1-A7, B1-B7, sA1-sA7, sB1-sB7. In these figures, intervehicle spacing was plotted versus time. The actual intervehicle spacing measured by the Rayelco instrument is shown by a dashed line and the corresponding radar reading by a solid line. These figures demonstrate the expected effect of losing the target when the relative speed between the two vehicles is close to zero.

5.2 Test results of the Amerigon radar.

In the sets of figures attached to the end of this report, (figures A1-A7, B1-B7, sA1-sA7, sB1-sB7), we are showing comparisons of the estimated target range as computed from the Amerigon radar data samples after applying our filter and the actual target range as measured by the reference sensor.

The indices used for numbering the figures follow the following simple logic:

The capital letter [A,B] indicates the type of algorithm used in filtering the data. The letter A indicates that during the “Masking” state of the envelope filter we applied infinite time constant (zero slope, 0 bits/sec), while the letter B indicates that we applied the same time constant (equal to 3 bits/sec) during the “Masking” and the “Sustain” state. Data were collected during seven test runs, and the number of the run is the second index used. To increase the resolution of the plotted data, we have broken up each run into segments. Each segment is 40 seconds long and is indicated by a lower case letter following the run number. The total duration of each run was different, so each run may consists of 2,3,4 or 5 segments. For example, figure A2c represents algorithm ‘A’, run ‘2’, segment ‘c’.

In all the figures, the estimated target range is shown by a solid line and the actual target range is shown by a broken (i.e. dashed) line. The measurement error is equal to the distance of the solid line from the dashed line at each sample point. Further insight is gained by looking at the actual data samples, the raw data coming from the radar. In the set of figures indicated by an ‘s’ prefix, (figures sA1-sA7, sB1-sB7) we are showing a comparison of the actual radar samples, the estimated target range as computed from these samples by applying the same filter type A or type B respectively and the actual target range as measured by the reference sensor. In these figures, the radar sample points are shown as round dots, the filtered radar range is shown by a solid line and the actual target range is shown by a dashed line. Due to the architecture of the radar, a target is usually detected by several range gates simultaneously, but it is usually the earliest reflections that represent the range of the target most accurately. To reduce the clutter of displaying all the dots in the figure, only one dot is shown for each sample period. It is the dot corresponding to the range gate that represents the minimum distance to the target.

5.3 Discussion and Recommendations

The results shown on the comparison plots, indicate that the greatest source of error in the range estimates from the Doppler based Amerigon radar is the fact that targets with no relative velocity or very small relative velocity cannot be detected. This is not due to hardware or software errors but it is a result of the principle of operation of this radar. The Amerigon radar relies on the Doppler effect which is known to have a limitation in detecting targets at very low relative velocities. This drawback could be reduced within the constraints of the initially proposed architecture. For example, while a stationary target (zero relative velocity) will forever remain invisible to Doppler radar, a target that moves at a very small relative velocity does not need to be. The Doppler effect from a slowly moving target simply generates a low frequency signal, which should be sufficient for detecting targets close to zero relative velocity.

The operating frequency of the Amerigon radar is 5.8 GHz which yields a Doppler effect of 17.28 Hz per mph. Even though at low Doppler frequencies the detection of such targets would involve a longer delay, their detection is theoretically possible. In the case of the Amerigon radar, a somewhat disappointing finding was that the implementation of the analog processing of the Doppler signals attenuates the low frequency response at frequencies less than about 10 Hz. This makes the detection of targets with relative velocity less than 0.58 mph rather unlikely. The lowest frequency observed in the data sets was about 7.2 Hz, corresponding to 0.43 mph. Targets at relative velocities less than 0.42 mph could not be detected. Furthermore, the simple rectification of the low frequency signal prevents the negative half cycle of the Doppler to be detected, effectively doubling the time interval during which a target with a relative velocity greater than 0.42 mph remains "invisible" for a time interval two times longer than the minimum possible. For example, a target with 0.42 mph relative velocity must be "masked" and "sustained" for 0.28 seconds, while full wave rectification of the same signal would only require masking for 0.14 seconds.

Another observed shortcoming of the Amerigon radar sample unit that we tested was an occasional but very apparent inability to resolve target range at the full five bits of resolution. Some times, there was an observed tendency to resolve range at only two bits of resolution, a significant rounding effect that significantly increased the measurement error. This happened frequently, as evidenced by the radar output data showing a strong clustering effect on certain ranges, appearing on the graphs as a horizontal line, while the actual position of the target was not near that line. This is visible in the attached figures (sA1 to sA7). This effect should not be confused with the effect of the data filter, which also results in horizontal line segments when the target relative velocity is near zero and the slope of the corresponding filter state is set to zero. This observation is only applicable to the horizontal line segments seen in those figures when the slope of the filter is non-zero.

This apparent non-linearity, the tendency of the output to "prefer" two bits resolution of range instead of five bits resolution of range can perhaps be explained by referring to the internal architecture of the Amerigon radar. There we can see that resolution over 32 ranges is achieved by four discrete processing blocks, each one assigned to resolve 8 adjacent ranges. Each one of the processing blocks employs different sensitivity to compensate for the fourth order law attenuation of radar return signals versus range. It seems that when the sensitivity of a processing block is set too high or conversely when the radar echo is too strong, a processing block can get overloaded and as a result all 8 range bins belonging to that processing block begin reporting the presence of a target, unable to further resolve the target to one of the 8 range bins within the block. It also seems, although it has not been systematically confirmed, that elevated temperatures increase the likelihood of appearance of this type of error.

While a reduction of sensitivity (which is a factory adjustable parameter) seems to be able to reduce or eliminate this problem, it comes at the expense of sensitivity to vehicles presenting a smaller radar cross section as well as increased likelihood of targets becoming "invisible" when their relative velocity becomes less than 0.58 mph. So this parameter becomes another candidate for "tweaking" before or during the experiments using the Amerigon radar a controller input. It should be noted though that the "rounding" effect we described may act as a stabilizing factor during vehicle following. So apart from the fact that it will result in position errors it may not have other adverse effects. Thankfully, the position error due to rounding is mostly on the negative side, i.e. it makes a target appear closer than it is, so it does not appear to be a serious collision risk.

6. Conclusions

A low cost radar developed by Amerigon corporation was calibrated and tested as a ranging sensor, in the laboratory and in an actual vehicle following situation. For tests in the laboratory, where the radar was stationary and the target was a moving aluminum foil pan, the radar met the performance specifications promised by the manufacturer for target distances of 9 feet to 17 feet when the relative motion velocity of the target was fairly greater than zero. When the velocity of motion of the target was close to zero, the radar failed to detect the target. In the vehicle following experiments performed at PATH, the test demonstrated that in a typical vehicle following situation the magnitude of the relative velocity is not sufficient for the radar to maintain a consistent and accurate detection of the relative position of the vehicle.

The performance of the radar could be improved by increasing the low frequency response of the detection circuits in order to be able to detect targets at lower relative velocities. According to the manufacturer, accuracy of the target measurements at ranges smaller than 9 feet could be improved by fine tuning the gains of the respective gate range circuitry.

Despite its drawbacks, the low cost of this radar is a significant consideration and its performance must be viewed in this light. It may have great applicability as a low cost redundant sensor working together with a different type sensor such as FMCW, to increase the confidence in the readings of the primary sensor and to provide fail safe redundancy in case of malfunction of the primary sensor.

7. Appendix A. (Filter source code)

```
#include <stdio.h>
#include <string.h>
/* This program processes the raw binary data from the Amerigon radar */
/* The input file is the raw data captured from the RS-232 */
/* The output file is the processed and filtered data */
/* For every sample, the output file has one line */
/* Each line contains an integer (1..34) representing the filtered */
/* range value plus a graphic that shows all 32 range bins */
/* An idle range bin is represented by a period "." /*
/* A range bin that is sensing a target is represented by "X" */
/* The closest range bin that is sensing a target is represented by "O"
*/
/* The filtered range bin is represented by "|" */
/* Written by Alexander Kanaris, February 6, 1997 */
/* For questions write to: kanaris@usc.edu */

FILE *ifp=stdin,*ofp=stdout;
char line[90]="line";
char rad[40]="radar";
int hitbin=34;
int realbin=34;
int decay=10;
long linecount=0;
float offset=0;

int getline(line, max)
char *line;
int max;
{
    if (fgets(line, max, ifp) == NULL)
    return 0;
    else
    return strlen(line);
}
void dispbin(val)
long val;
{
    int i;
    int hit;
    unsigned long mask;
    mask=0x80000000;
    hit=0;
    realbin=40;

    for (i=0;i<34;i++)
    {
        if (val & mask)
        {
            if (!hit)
            {
                rad[i]='O';
                realbin=i+1;
                if (i < hitbin)
                {
                    hitbin--;
                    decay=40;
                }
                if (i==hitbin)
                {
```

```
                    decay=160;
                }
            }
            else
            {
                rad[i]='X';
            }
            hit=1;
        }
        else
        {
            rad[i]='.';
        }
        mask >>= 1;
    }
    if (hit==1)
    {
        decay--;
    }
    if (decay==0)
    {
        hitbin++;
        decay=30;
    }
    if (hitbin<34)
    {
        rad[hitbin]='|';
        /* The following line prints the range bin number */
        /* There are 32 ranges, plus 2 from extrapolation */
        /* Result is in the range 1 to 34 */
        fprintf(ofp,"%lf %2d ",offset+linecount*0.0041,hitbin+1);
    }
    else
    {
        hitbin=34;
        /* The "--" symbol represents the target out of range condition
*/
        /* Substitute with spaces, i.e. "  " if necessary */
        fprintf(ofp,"%lf NaN",offset+linecount*0.0041);
    }
    /* This cancels the "range bin" part of the display */
    /* fprintf(ofp,"%s%s",rad,"\n"); */

    if (realbin==40)
    {
        fprintf(ofp," NaN \n");
    }
    else
    {
        fprintf(ofp,"%2d \n",realbin);
    }

}
int extractvalue(line)
char *line;
{
    char *p,*q,*r;
    char letr;
    p=strchr(line,'\n');
    sprintf(p," ");
    /*
    for (q=p;q>=line;q--)
    {
        letr=*q;
```

```
        if (letr >= 'A' && letr <= 'Z')
        {
            r=q;
            break;
        }
    }
    fprintf(ofp,"%s%s",r,line);
    */
    return 1;
}

main(argc,argv)
int argc;
char *argv[];
{
    int c,d,firstline;
    char *p,*q,*r;
    char letr;
    long value;

    if (argc >1)  /* input file name has been given */
    if ((ifp=fopen(argv[1],"rb"))==NULL)
    {
        printf("Can not open file \"%s\", for
input.\nExiting\n",argv[1]);
        return 1;
    }
    if (argc >2)  /* output file name has been given */
    if ((ofp=fopen(argv[2],"wb"))==NULL)
    {
        printf("Can not open file \"%s\", for
output.\nExiting\n",argv[2]);
        return 1;
    }
    printf("Offset = ? ");
    scanf("%f",&offset);
    printf("\nThe Offset will be: %f ",offset);

    while ((c=getc(ifp)) !=EOF)
    {
        ungetc(c,ifp);
        value=0;
        while ((c=getc(ifp)) != 0xAA && c != EOF)
        {
            value <<=8;
            value |= c;
        }
        /* printf("%lX ",value); */
        dispbin(value);
        linecount++;
    }

    fclose(ifp);
    fclose(ofp);
    printf("Done \n");
    printf("\nTotal time: %f seconds.\n",(float) linecount*0.0041);
    /* printf("\nTurbo C coding by Alexander Kanaris, Feb. 1996\n");*/
    return 0;
}
```

8. Appendix B. (Test results plots)

In the attached set of figures, (figures A1-A7, B1-B7, sA1-sA7, sB1-sB7), we are showing comparisons of the estimated target range as computed from the Amerigon radar data samples after applying our filter and the actual target range as measured by the reference sensor. A detailed explanation of the content of the figures has been given in section 5.2. The figures do not have page numbers because they were produced by Matlab. Instead they have been ordered by figure number.

9. References

[1]. Mealy, G.H., “A Method for synthesizing Sequential Circuits,” Bell System Technical Journal, vol. 34, pp. 1054-1079, September 1955.

[2]. Friedman A.D., Menon P.R.. “Theory & Design of Switching Circuits,” Computer Science Press, 1975.

Figures and Tables.