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J. Justiss, S. Levinson, and R. Russell

Institute for Advanced Technology
The University of Texas at Austin

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MICROWAVE DOPPLER MEASUREMENTS OF PROJECTILE VELOCITY IN A SINGLE-STAGE GAS GUN

J. Justiss, S. Levinson, and R. Russell

Institute for Advanced Technology, Austin, Texas

Abstract—A microwave-frequency Doppler system was developed and implemented in a single-stage gas gun to develop an in-bore velocity profile. The technique uses a 24.15 GHz microwave transceiver to measure the Doppler frequency change as the projectile travels down the bore. The difference of the source signal and the shifted signal was digitally extracted by a mixer and recorded by a digital oscilloscope. From each recorded signal, the Doppler frequency shift information was deduced, providing a detailed projectile velocity profile of each shot.

INTRODUCTION

Velocity measurements in gas guns are typically performed with break screens. This method provides only a moderate number of time-of-flight samples, which can unnecessarily limit insight into the interior ballistics of a shot process. Using microwaves to record the velocity of a projectile (via Doppler shift) during launch is a method that provides a large number of accurate temporal samples of the velocity profile.

A M/A-COM Gunnplexer is a microwave transceiver and mixer and was the heart of the microwave system used in this investigation. A Gunnplexer will produce a microwave signal nominally in the X or K band with its main Gunn diode. It uses a second diode to receive the incoming signal. The original signal is then mixed in a Schottky diode with the incoming signal. This mixing results in a signal that is the difference in frequency of the two wave forms and referred to as the modulation signal. In the application described in this technical note, the modulation signal comes directly from the velocity of the projectile. Gunnplexers offer a cheap means of recording the Doppler shift created by launched projectiles.

Knowing the velocity during the entirety of a shot can be a very powerful tool. However, data that is even more interesting can be extracted from accurate, densely populated velocity plots. Integration of the velocity provides position profiles, and modified differentiation of the velocity yields acceleration profiles with relatively low error. With these three basic plots—velocity, position, and acceleration profiles—changes in bore diameter can be evaluated in some detail. The mechanics of a launch are also indicated, and peak pressure and jerk can be calculated and used to improve projectile/sabot design.

The general purpose of this work is to understand the advantages and problems associated with using microwave technology to measure projectile velocity in experimental guns and to develop proficiency with the technique so that the feasibility of more complicated measurements using microwaves (e.g., in-bore transverse velocity) can be evaluated. This technical note

describes an initial investigation of the theoretical and experimental aspects of how microwave technology was used to measure a projectile's velocity in shots that ranged from 10m/s to more than 250 m/s.

THEORY

A schematic view of the microwave velocimeter is shown in Figure 1. A sinusoidal microwave signal projects from a source antenna (horn), propagates up-range into the barrel of the gun, reflects off of the leading edge of the traveling projectile, and is collected by a receiving antenna. With the appropriate coupling components, the receiving and transmitting antennae can be the same. The frequency of the reflected signal experiences a Doppler shift and is directly related to the velocity of the projectile. Samples of the source signal and of the received, reflected signal are applied to a square-law detector, which provides as output only the Doppler frequency component of the signal. The Doppler frequency (or projectile velocity) component is recorded directly with a digital oscilloscope.

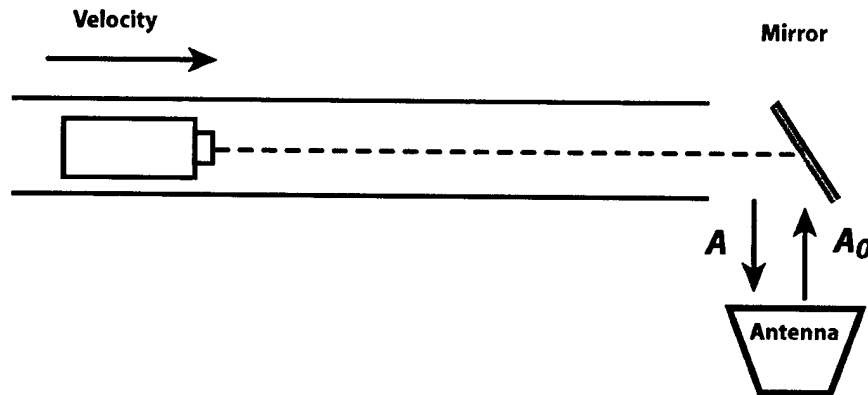


Fig. 1. This figure shows the theoretical setup of the microwave velocimeter. A microwave signal A_0 is transmitted as a wave by the antenna, reflected off of the mirror, and directed into the barrel up-range to strike the projectile. A fraction of this wave reflects off of the moving projectile and travels down-range to reflect off of the mirror, which directs it into the antenna. The wave fraction is received by the antenna as signal A .

In a two-wire transmission line, signals will propagate as transverse electromagnetic (TEM) waves longitudinally along the axis of the line. TEM waves will not propagate inside the bore of a round- or square-bored wave guide. Only very high-frequency transverse electric (TE) or transverse magnetic (TM) modes will propagate inside the bore [1]. Inside the wave guide, several modes may be present, and at any given time or position in the barrel they may interfere; but usually the lowest-order (lowest-frequency) mode is dominant. While single-frequency microwaves are inside the bore of the gun, they propagate as either TE or TM waves, or as both, and will travel longitudinally along the bore axis (like TEM waves) in either or both directions. Doppler frequency shifts occur anytime that a traveling wave reflects or is produced by a moving object. A Doppler phase shift may be calculated as follows:

$$A_0 = a_0 \sin(\omega_c t + \theta)$$

$$A = a \sin(\omega_c t + \theta + 2kL)$$

Where, A_0 = the original signal, A = the reflected signal, and $\omega_c = 2\pi f_c$ with carrier frequency f_c and time t . A constant wavelength $k = \omega_c / c$ (for air-filled bores) is the ratio of the carrier frequency and speed of light constant c . The phase $2kL$ of the reflected signal undergoes a change proportional to the wave travel distance or twice the projectile position $L=vt$; where v is the velocity of the projectile.

The signals may be added and squared (or mixed) to detect the Doppler shift:

$$\begin{aligned} (A_0 + A)^2 &= [a_0 \sin(\omega_c t + \theta) + a \sin(\omega_c t + \theta + 2kL)]^2 \\ &= a_0^2 \sin^2(\omega_c t + \theta) + a^2 \sin^2(\omega_c t + \theta + 2kL) + 2a_0 a \sin(\omega_c t + \theta + 2kL) \sin(\omega_c t + \theta) \end{aligned}$$

This mixed signal can be expanded in functions-of-time terms described by:

- (1) Zero frequency (DC),
- (2) Frequencies that are multiples of the carrier frequency ($\geq f_c$), and
- (3) An intermediate frequency (IF)—which is usually significantly smaller than the carrier frequency f_c .

Terms (1) and (2) contain DC (a constant) and a multiple of the carrier frequency (high-frequency) terms and may easily be removed by filtering. Term (3) may be expanded using trigonometry difference properties:

$$\begin{aligned} &2a_0 a \sin(\omega_c t + \theta + 2kL) \sin(\omega_c t + \theta) \\ &= a_0 a \cos(\omega_c t + \theta + 2kL - \omega_c t - \theta) - a_0 a \cos(\omega_c t + \theta + 2kL + \omega_c t + \theta) \\ &= a_0 a \cos(2kL) + a_0 a \cos(2\omega_c t + 2\theta + 2kL) \end{aligned}$$

Since ω_c can be made—and for microwaves, *is*—very large, the second term above may be easily filtered, leaving only the first term:

$$S_{IF} = a_0 a \cos(2kL) = a_0 a \cos\left(\frac{4\pi f_c vt}{c}\right) = a_0 a \cos(2\pi f_e t)$$

This relatively low, intermediate frequency (IF) signal is the output of the mixer—and the projectile velocity v is directly proportional to its effective frequency f_e :

$$v = \frac{f_e c}{2f_c}$$

EXPERIMENTAL SETUP

Microwave velocity measurements were performed on a single-stage light gas gun at the Institute for Advanced Technology (IAT) in Austin, Texas. This gun has a barrel length of 5 meters and an inner diameter of 56 millimeters. The lower ranges of TE and TM modes were present when the 24.415 GHz source signal was used. These include: TE_{12} , TE_{01} , TM_{01} , TM_{02} , TE_{02} , TM_{11} , and the dominant mode: TE_{11} . Shots on this gun routinely reach a nominal velocity of 250 m/s. The single-stage gas gun also can provide shots at extremely low velocities—approximately 10 m/s. For the low-velocity shots, a Lexan projectile 56 mm in diameter was used as the breech. One advantage of low-velocity shots is that they can be repeated quickly.

The microwaves were produced by the microwave velocimeter, directed by a horn antenna, and reflected by a mirror; the microwaves were then Doppler-shifted by the projectile and returned along the same path. The mirror was a 1/8" aluminum plate, and the projectile was a Lexan cylinder with a 1/4" aluminum flyer plate affixed to the front. After the antenna received the Doppler-shifted, reflected wave, the wave was combined in the mixer with the source wave. The IF signal was measured and recorded by a digital oscilloscope. (A laser-based velocimeter system at the muzzle was used to trigger the oscilloscope.) The projectile had five reflective rings at known intervals along the surface to reflect the laser. When the laser was reflected, peaks were recorded on the oscilloscope and were used to measure muzzle exit velocities.

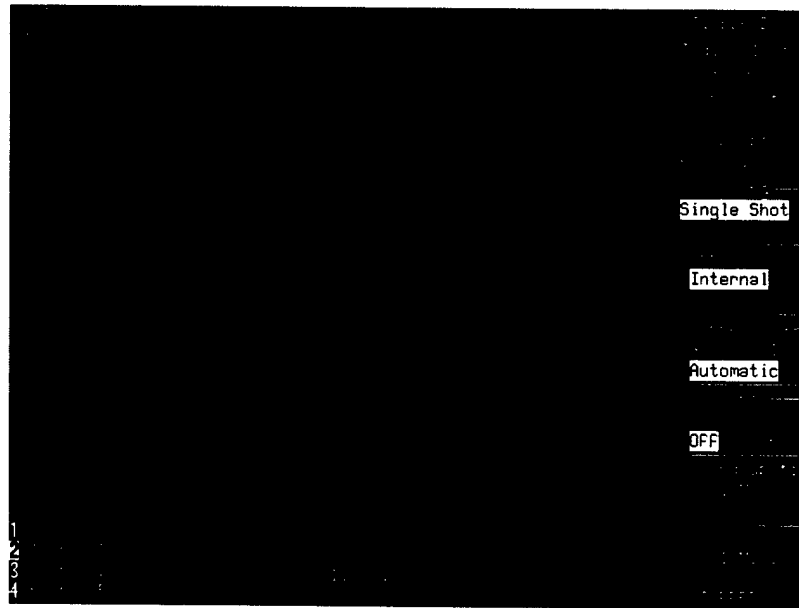


Fig. 2. This figure shows the oscilloscope readout for a shot. The microwave data appears in magenta, while the laser trigger data appears in teal. The shot lasted approximately 3.9 seconds.

A Gunn diode produced a source signal that was split into two paths. One path was directed to the horn antenna and into the bore to propagate along the pre-described path. The other path was used in the square-law detector to mix the modulated signal.

Figures 3 and 4 illustrate the setup of the instrumentation tank and the horn antenna. The mirror is on a freestanding base. This is possible because the instrumentation tank is evacuated, and subsequently, there is no air column being pushed down range by the projectile. If a vacuum is not pulled, then a stronger anchor needs to be attached to the mirror.

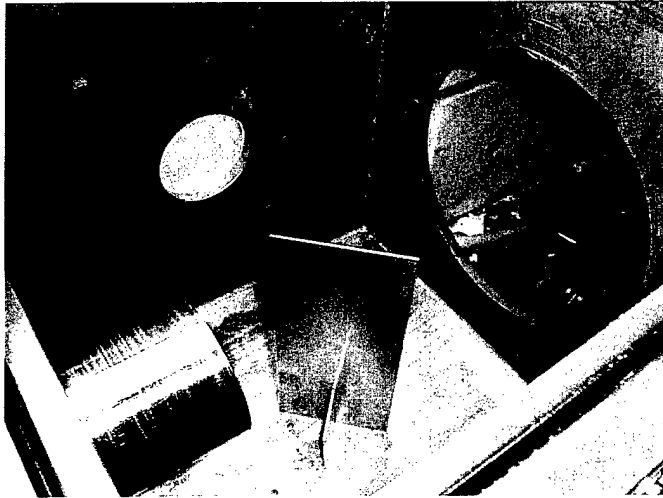


Fig. 3. In this photo, the muzzle appears on the left and the mirror appears in the center. The mirror was aligned with a laser to direct the electromagnetic waves onto the microwave velocimeter; this does not appear in the photo.

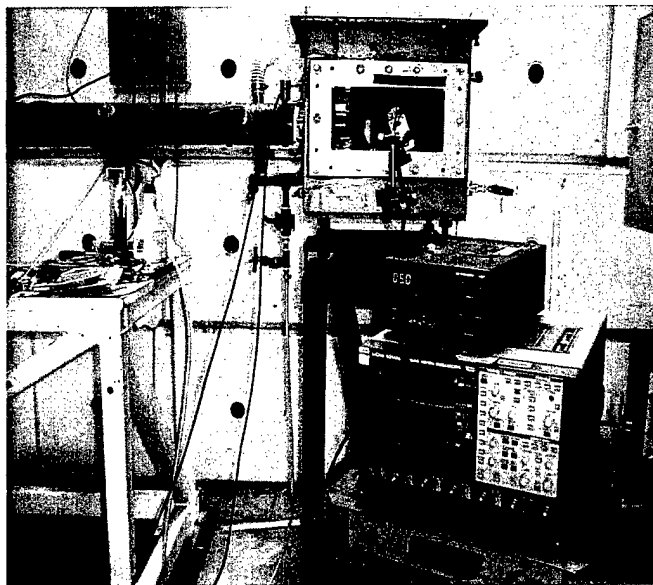


Fig. 4. This photo shows the muzzle of the single-stage gas gun, the microwave velocimeter and power supply, and measurement equipment. The microwave velocimeter resides outside of a Plexiglas window in front of the bore.

LOW-VELOCITY SHOTS

One focus of this investigation was low-velocity shots. These were performed as preliminary experiments to test the feasibility of the design for a velocimeter. A stream of compressed air (100 psi) was directed into the breech continuously behind the projectile. The projectile attained velocities just below 10 m/s, and most of the acceleration occurred within the last half-meter of the barrel.

Figures 5–8 illustrate how the Doppler frequency information was processed to yield the velocity profile for a low-velocity shot. Details of the processing are provided in the captions. Figure 5 shows the initial set of data, recorded before any processing has occurred. Figure 6 shows the periodic nature and increasing frequency of the shot. Figure 7 shows the linear interpolation method used to find the zero crossings. Figure 8 is the final velocity-versus-time plot.

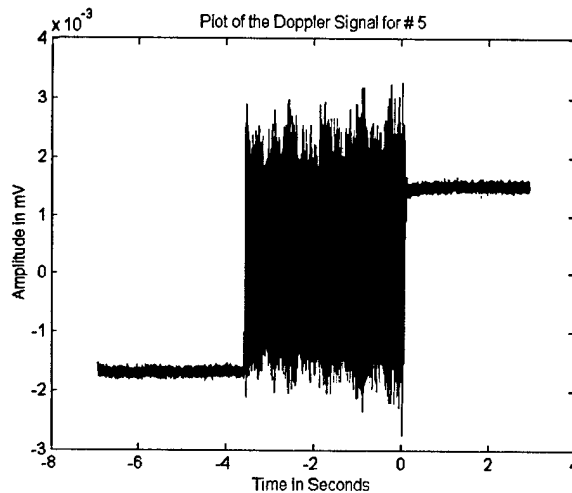


Fig. 5. The data was highly over-sampled, so it was reduced from 1 mega sample/sec to 5000 samples/sec. The process used also averaged the data to produce a smoother curve.

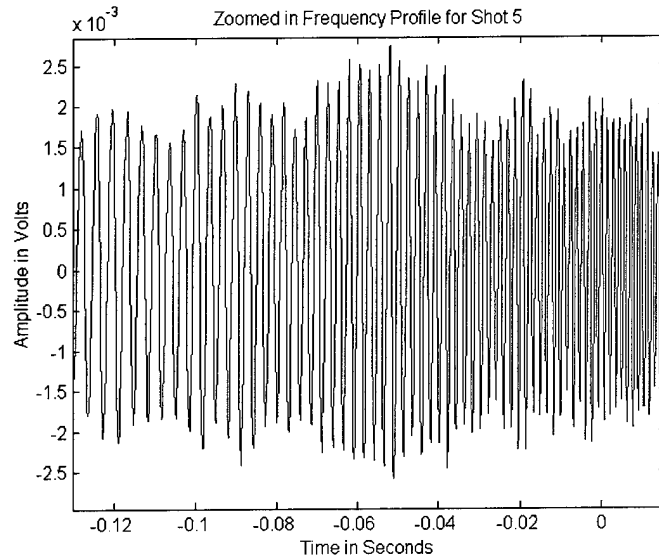


Fig. 6. This figure shows a zoomed-in view of the IF signal. One of the main concerns was whether the data would have obvious interference from the various TE and TM modes that propagated in the bore. The data, however, shows a very smooth sine wave structure with a varying frequency.

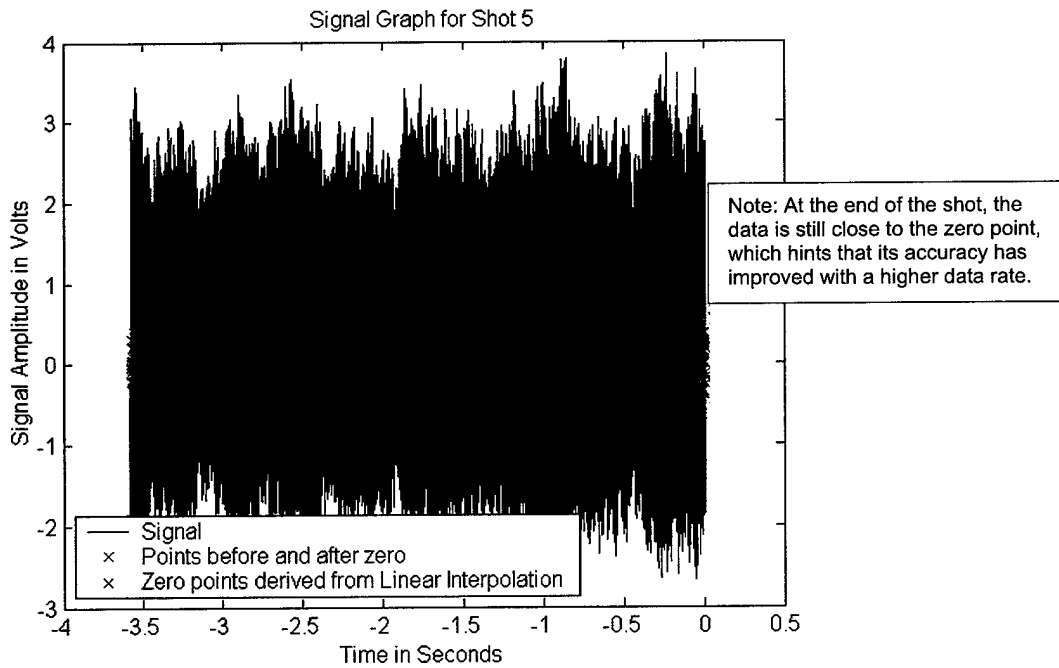


Fig. 7. The mean of the sine-wave-like signal was first subtracted to center it at 0 voltage (blue curve). Pairs of points on the renormalized signal that occur in time just before and just after a zero crossing were then recorded and appear as green crosses. From these pairs, more accurate zero crossings were determined and appear in red. The time differences of adjacent zero crossings establish half-wavelengths, from which a time-varying frequency f_c and projectile velocity v was calculated.

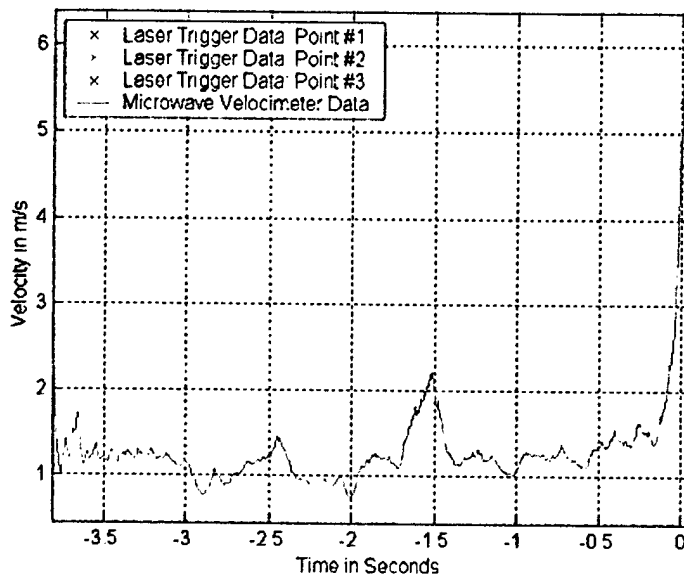


Fig. 8. This figure shows the velocity-versus-time graph. After the velocity profile was attained, accuracy still had to be determined. The velocity was verified at three points by a laser-triggering program at the end of the shot ($t=0$). The projectile had five reflective bands along the outer circumference, and since the distance between these bands was known and the time intervals could be determined on the oscilloscope, a $\Delta d/\Delta t$ velocity could be determined. The ratio of difference between the two methods was less than .005.

The low-velocity shots proved that the microwave velocimetry method is indeed feasible. Microwave velocity measurements were corroborated using a laser bar-code scanner, and were acceptable under the conditions in place. Resolution was poor for the low-velocity shots because of the long sine wave periods associated with slow velocity. At higher velocities, poor resolution was not an issue.

250 M/S SHOTS

The 250 m/s shots were conducted from August 2002 to March 2003. The same processing techniques were used for the 250 m/s shots as for the low-velocity shots, but slightly different results were obtained. The data rate (or the amount of data collected) was much higher for 250 m/s shots because the 10 kHz Doppler signal associated with this velocity provided 1000 times more zero-crossings than the 10 Hz Doppler signal associated with the low-velocity shots. As a result, the velocity profiles had much greater detail, allowing a larger degree of averaging to reduce noise than for corresponding low-velocity shots, as shown in Figure 9. This effect is expected to continue at still higher speeds (e.g., 2.5 km/s and beyond).

Additionally, position and acceleration profiles were created. (These procedures were not performed on the low-velocity shots.) The position profiles, like the one shown in Figure 10, provided another verification of the accuracy of the microwave velocimeter. The bore of the gun is approximately 5 meters long. When the first shots were performed, position data also showed that the projectiles traveled approximately 5 meters. These data also revealed a potential problem with the gun launch procedures. The microwave velocimeter showed that projectiles

were being pulled down-range when the range was evacuated. This finding prompted the establishment of a tethering system to restrain the projectile before launch.

Acceleration estimates were calculated from accurate, low-order polynomial fits of the microwave velocity measurements. The acceleration plots, such as the one shown in Figure 11, implied that a flaw in the bore was present about 75 cm downrange of the bore. Analysis of the acceleration provided an independent confirmation of a pressure transducer reading in the breech at early times. The pressure transducer and the microwave velocimeter's acceleration estimates were consistent when the base of the projectile was in close proximity to the pressure transducer. However, at a later time, the acceleration estimates from the pressure transducer measurements were 50% lower than the velocity estimates provided by both the laser and microwave velocimeters—which agreed within 0.5% at muzzle exit. These results indicate that the pressure transducer, fixed near the breech, was an unreliable measurement of the base pressure of the projectile at later times of the single-stage gunshots.

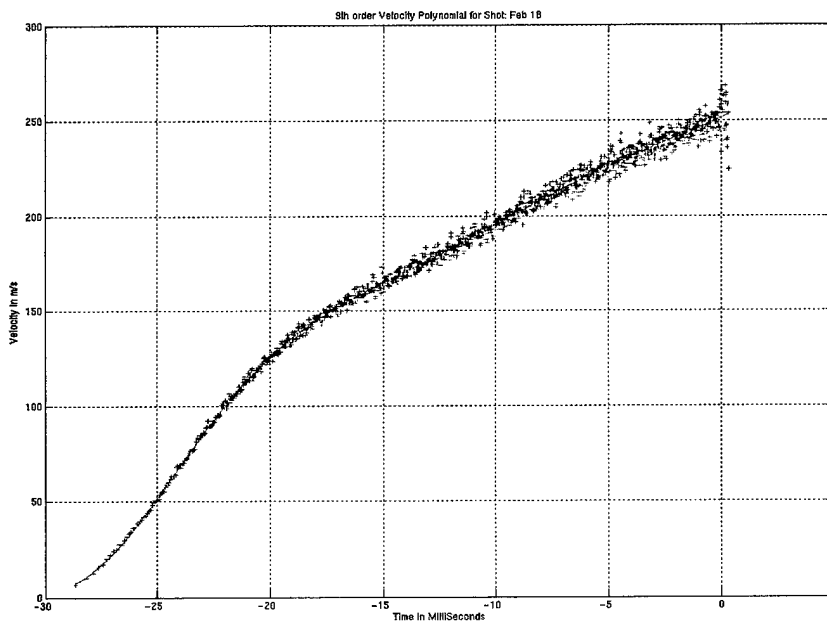


Fig. 9. The data from the higher-velocity shots show increases in data density and accuracy. With these higher data densities, imperfections in the gun and gun mechanics can be seen and analyzed.

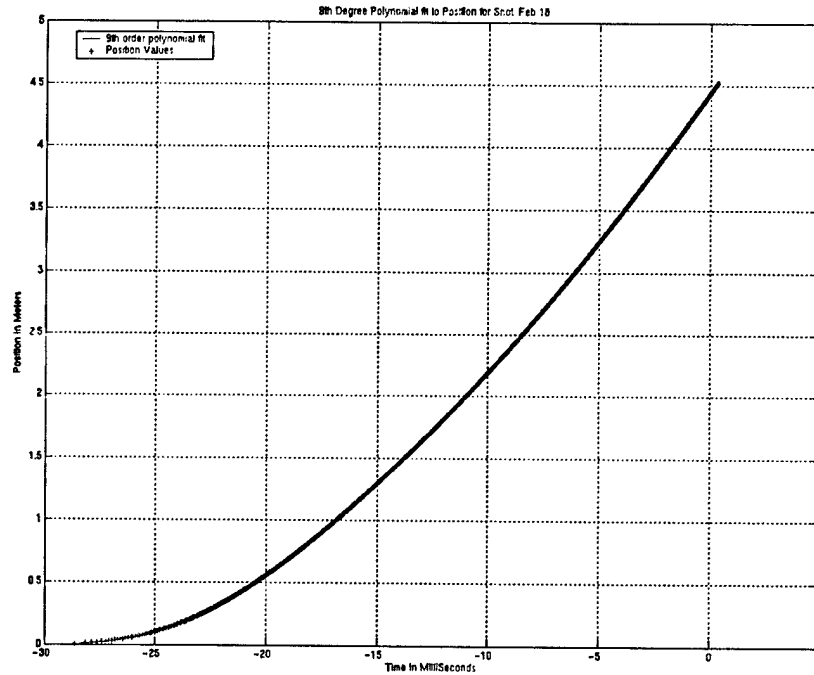


Fig. 10. The velocity profile was integrated via trapezoids to produce a position profile. The position profile was used to verify the accuracy of the gun. The total length traveled in this experiment was approximately 4.5 meters. The microwave velocimeter verifies the physical measurement taken before the shot.

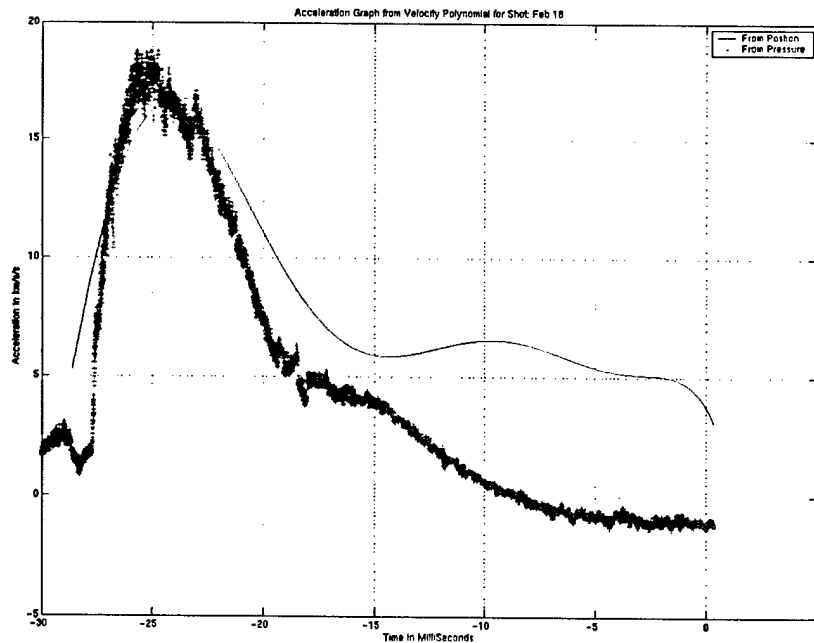


Fig. 11. The blue line shows acceleration from the microwave velocimeter, and the green line shows acceleration derived from a pressure transducer. The velocity profile is differentiated to produce an acceleration plot. The acceleration also verifies the microwave velocimeter measurements. The base of the projectile uncovers the pressure transducer at -27 ms, at which time the two values are within error tolerances. The acceleration plot can also be used to calculate the base pressure of the projectile.

DISCUSSION

The microwave velocimeter suffered poor resolution for low-velocity shots since the wavelength (or sine-wave periods) is impractically large. There are two solutions to the problem of low resolution at low velocities: one is a data processing technique, and the other is a modulation solution.

The data processing technique involves fitting sine waves over small time intervals. Since each point of the data was originally part of a sine wave, that original sine wave should retain much of its original form over short time intervals. Over these intervals, a signal could be expressed in the form: $s(t) = d + A\sin(x + vt + at^2 + bt^3)$, where d is the vertical offset, A is the amplitude, x is constant phase shift, v is the instantaneous velocity, a is the instantaneous acceleration, and b is the instantaneous rate of change in acceleration. This method would not only calculate the velocity more accurately, it would also allow one to obtain the position and acceleration profiles. In addition, there is potential for significant improvement in resolution and accuracy at very low velocities. This technique suffers, however, from any noise, which is never fully eliminated from the waveform. Noise greatly biases estimates of the coefficients in $s(t)$. Therefore, it is recommended that the technique only be used in sections of a shot that cannot be processed by the second solution (described below).

The second solution involves modulating the IF signal with a sine wave with constant frequency f_{mod} . The source signal would then take the form of $s(t) = d + A\sin(\theta_m + 2\pi f_{\text{mod}} t)$, where f_{mod} is the modulation frequency and θ_m is a phase shift caused by the Doppler shift in frequency associated with projectile motion. By shifting the signal frequency up by f_{mod} in this manner, the long periods between zero crossings associated with low velocities would be reduced accordingly, and the resolution of the microwave system would be correspondingly improved. A drawback of this method is the need of highly accurate and precise equipment because the added complexity of the system introduces additional noise and uncertainty.

CONCLUSIONS

The microwave velocimeter analysis has been applied in only a limited way to a gas gun. The microwave velocimeter has additional applications, such as the improvement of gun codes and design procedures. As a preliminary study, the microwave velocimeter has shown significant potential for application on the various launchers at the IAT, and particularly for the two-stage light gas gun.

Using microwaves to determine the velocity of a projectile while in-bore has proven to be an accurate means of attaining a velocity profile. This technical note describes tests that were performed at relatively low velocities, but in principal, there is no practical velocity threshold above which the accuracy of tests is limited. The device used to collect the single-stage gas gun data has been proven to accurately gather velocity measurements up to speeds in excess of 250 m/s. Data processing techniques that have the potential for even greater accuracy and resolution exist. The microwave velocimeter has been made cheaper and more accurate in recent years. This work has shown that it has great potential for providing insight into gas gun experiments.

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