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Registered Frequency-Stepped Radar Data Collected on a Maneuvering Pickup Truck at K_a-Band

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Abstract

Two-dimensional inverse synthetic aperture radar (ISAR) imagery can be generated with a stationary radar illuminating a moving target. Data were collected on a 1994 Chevy Cheyenne 1500 series pickup as it was slowly pulled through a stationary radar beam to help analyze noncooperative ISAR algorithms. The speed of the vehicle varied from constant velocity to constant acceleration and the turning angle of the wheels was constant. The radar was a frequency-agile, coherent, pulsed K_a-band instrumentation radar built by the U.S. Army Research Laboratory (ARL). The data were registered optically and with stationary and rotating reflectors.

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Introduction

Real-beam radars have been used for many years to detect and track moving targets, but they have had limited success with the identification of targets. Typically, the input to a target identification algorithm from a real-beam radar has been one-dimensional (1-D) high-range-resolution (HRR) profiles. Two-dimensional high-resolution imagery from a real-beam radar is more difficult to generate, but it has the potential to greatly improve automatic target recognition (ATR) algorithm performance.

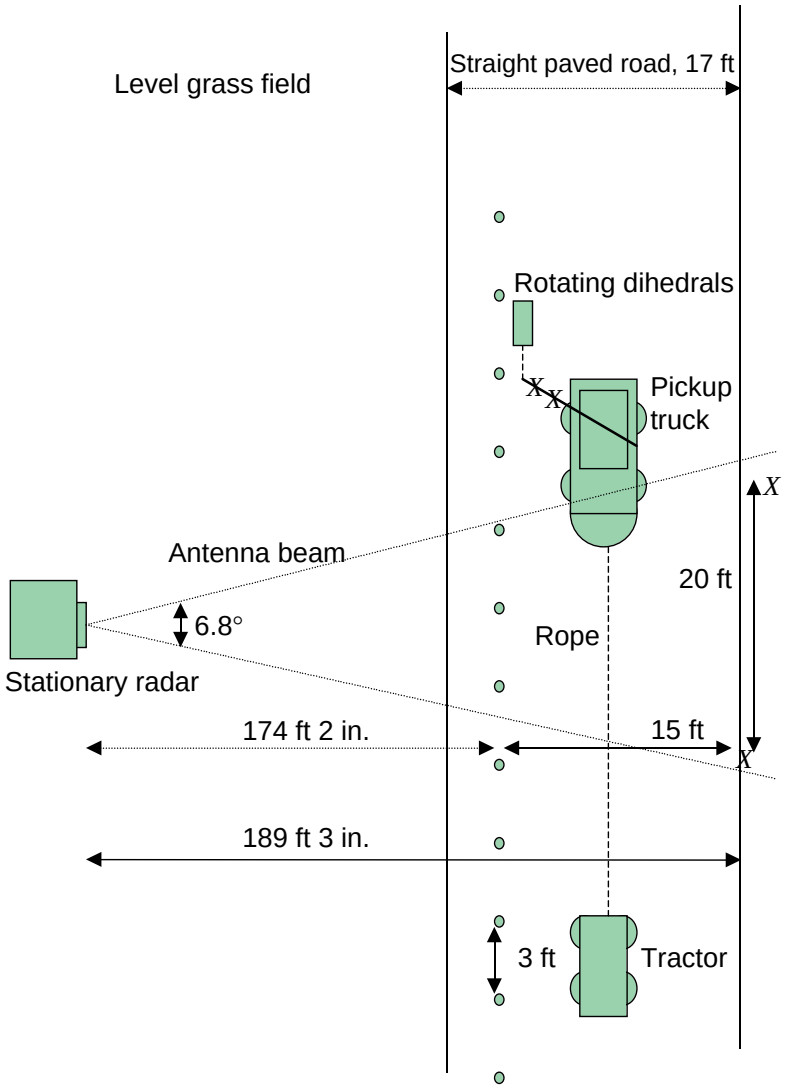
Synthetic aperture radar (SAR) techniques have been extensively studied, and many SAR systems have been successfully implemented that generate high-resolution 2-D imagery. The synthetic aperture is typically generated by a side-looking radar within an airplane that is flying in a straight trajectory. The basic scenario that describes noncooperative inverse synthetic aperture radar (ISAR) data collection consists of a stationary radar that illuminates a moving target. The radar could be tracking the target or the radar could be pointed at a fixed location with a target driving through the radar beam. In either case, the processing techniques are very similar. A basic processing technique for SAR/ISAR is range-Doppler imaging [1,2]. This technique does not generate optimally focused imagery, but at high frequencies, focusing errors are small and it is computationally efficient. In general, a high ratio of crossrange to downrange motion is desirable.

ISAR images generated with a radar operating at millimeter-wave (MMW) frequencies have advantages and disadvantages over images generated with longer wavelengths. The image resolution in the crossrange direction is proportional to frequency, so higher resolution images can be generated with a higher frequency radar. At higher frequencies, a larger frequency bandwidth is usually available, so higher downrange resolution can also be achieved. The major disadvantages of operating at higher frequencies are increased cost and reduced power. Also, high-frequency radar returns are more sensitive to small changes in the aspect angle of the target.

Measurement

Radar data were collected for testing noncooperative ISAR algorithms at range 8 at Aberdeen Proving Ground, MD, on 24 September 1998. Figure 1 shows the setup of the radar, target, and registration reflectors. A John Deere tractor was used to slowly pull a 1994 Chevy Cheyenne 1500 series pickup truck on a paved road through the radar beam. (We used a tractor because it could maintain a slow speed easier than the pickup.) A 50-ft rope was attached between the tractor and the pickup truck. The radar illuminated a fixed volume and did not track the target.

Figure 1. Setup for noncooperative ISAR measurements.



Note: *X* denotes trihedral reflector;
o denotes styrofoam cup.

Radar Characteristics

The U.S. Army Research Laboratory (ARL) has a coherent fully polarimetric radar system capable of operation at *X*-band, K_a-band, or *W*-band [3]. Table 1 lists the characteristics of the K_a-band radar system that was used to measure the test target.

The in-phase and quadrature (I&Q) outputs of the system are sampled with a 12-bit analog-to-digital (A/D) converter for each pulse. Four A/D converters sample the vertical and horizontal I&Q returns from vertically (V) and horizontally (H) transmitted pulses for 256 stepped frequencies. Data are averaged over pulse groups and stored as 256 I&Q pairs for both the vertical and horizontal receive channels.

For this measurement, data were collected synchronously, but not uniformly. Conceptually, two streams of data were collected at sample intervals of 50 ms. The streams were separated in time by 16.6 ms. The radar is fully polarimetric, but only transmit vertical, receive vertical (VV) polarization was recorded due to field test requirements. The data were calibrated using software developed by the Millimeter-Wave Branch at Aberdeen Proving Ground, MD [4].

Table 1. Radar characteristics at K_a -band.

Characteristic	Value
Maximum frequency	34.8 GHz
Minimum frequency	33.2 GHz
rf bandwidth	1.6 GHz
Frequency step	6.3 MHz
Peak transmitted power	+20 dBm
Pulsewidth	100 ns
Pulse repetition frequency (PRF)	1.0 MHz
Transmitted polarization	V or H
Received polarization	V and H
3-dB beamwidth (one way)	8.6°
System noise figure	9 dB (single sideband)
Polarization isolation	25 dB

Registration

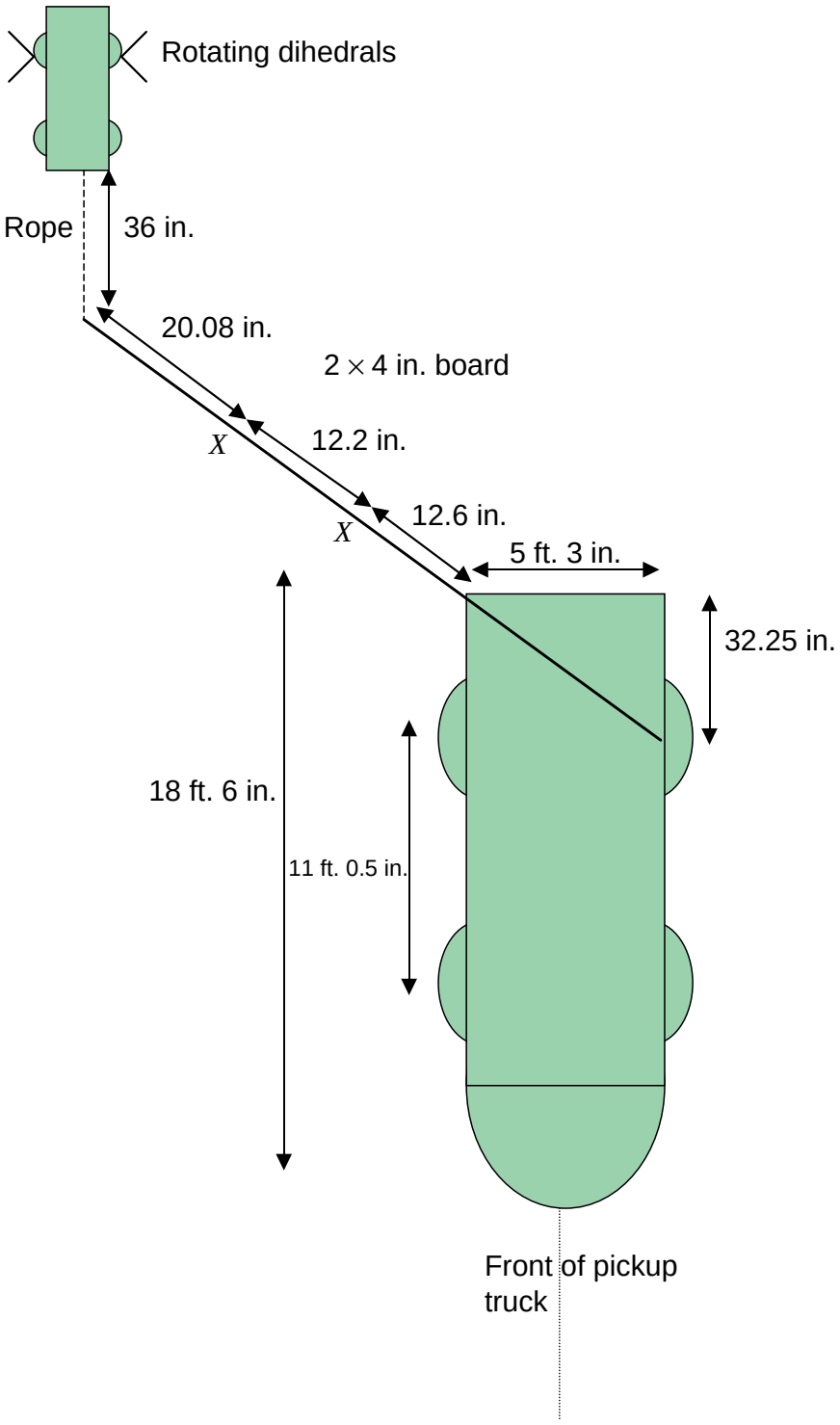
The measurements were registered using an optical video camera with a zoom lens and several radar reflectors. The video camera was mounted on the radar. Styrofoam cups visible to the camera were placed at 3-ft intervals along the road. The cups were approximately 18 in. from the edge of the road that was closest to the radar. Trihedral reflectors were placed slightly beyond the road and 20 ft apart. The two-way 3-dB beamwidth of the radar at this range was approximately 21 ft. The radar cross section (RCS) of the trihedrals were 14.6 and 16.5 dBsm at 34 GHz; however, they were only visually aligned with the radar. The heights of the reflectors were slightly lower than the height of the hood of the pickup truck.

Radar reflectors and masking tape were used to register the location of the pickup truck. Their relative positions, described in units of feet and inches, are shown in figure 2. The pickup truck was marked with 4-ft vertical strips of tape at the center of each wheel. The tape was broken, so the wheels could turn freely. A reflector array mounted on a 2×4 in. board was placed across the bed of the truck. The array consisted of two trihedral reflectors mounted at the positions indicated in figure 2 and a mobile radar registration reflector (MRRR) attached with a string to the end of the 2×4 in. board. The RCS of the trihedral reflectors was approximately 1.3 dBsm at 34 GHz. The reflector array was positioned so that it could easily be cropped out of the image. Measurements of the target were made with and without the reflector array.

The MRRR is a skateboard with a small dihedral reflector mounted on each rear wheel. Figure 3 is a picture of the reflector. Radar absorbing material was glued to the skateboard to reduce returns from the support structure for the wheels. The RCS of the dihedrals was approximately –4 dBsm at 34 GHz. The radius of the wheels was approximately 0.979 in. The rotating dihedrals will produce a modulated radar return that can be fit to determine the position of the MRRR. The position of the MRRR can be used to help estimate the position of the pickup truck.

Figure 4 is a picture of the target with optical registration and radar reflectors taken from the video camera that was mounted on the radar. In the run selected, a speed bump was placed on the road. The speed bump can be seen directly below the intersection of the pickup truck cab and the bed. Time was also recorded, but it is cropped out of the image.

Figure 2. Registration of pickup truck.



Notes: *X* denotes trihedral reflector.

Figure 3. Mobile radar registration reflector.

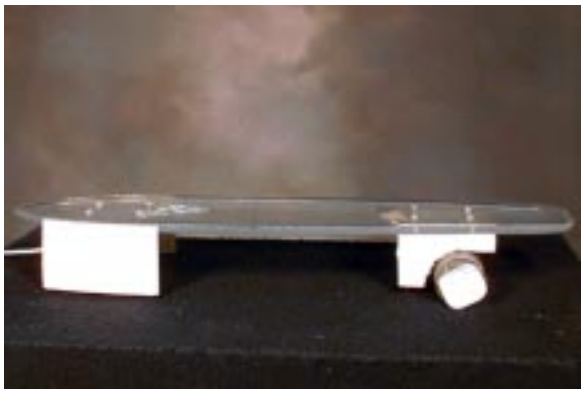
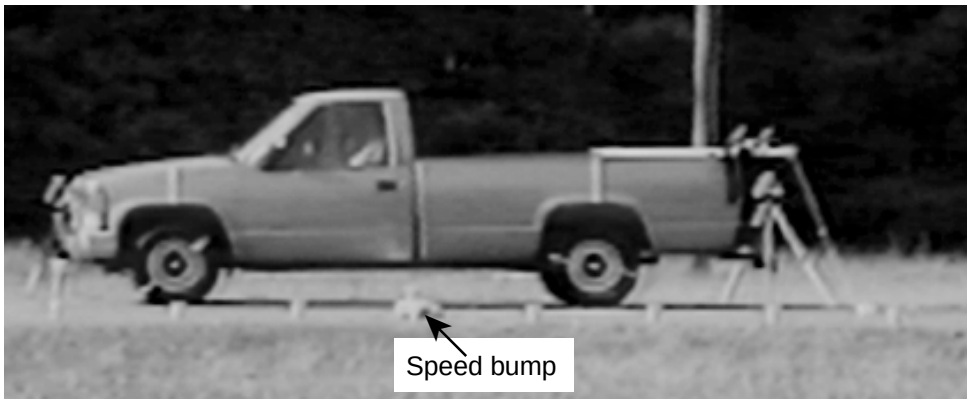


Figure 4. Optical image of target obtained from video camera tape.



Target Motion

Radar data were collected for various target trajectories. The speed of the pickup truck was controlled by the person driving the tractor. The goal of the tractor driver was to maintain a speed with either constant velocity or constant acceleration, depending on the selected scenario. The steering wheel of the pickup was controlled by a person. The goal of this person was to keep the angle of the front wheels constant while keeping the vehicle on the road. Turns were initiated when the front of the vehicle crossed the leading 3-dB beamwidth of the radar and stopped when the end of the vehicle crossed the trailing 3-dB beamwidth of the radar. Table 2 contains some approximations of the motion parameters of the target.

Two runs were made with the target going over a speed bump. The speed bump was used to introduce a controlled 3-D perturbation to the motion of the target. The speed bump was 8 in. long and 3-1/2 in. high. The motion of the target was dramatically changed by the bumps. It slowed down while attempting to go over the bump, and it sped up after it cleared the top of the bump. While most of the runs were made with the registration reflector array on the target, several runs were made without it. Table 3 describes the target motion, registration, and potential problems for each run. The data files were stored in ASCII format. The first column of the data file is the time in milliseconds. The second and third columns are I&Q values, which are associated with a specific radar frequency. There are 256 frequencies that were monotonically stepped and recorded. The registration field indicates whether the reflector array was secured to the pickup. The time that the video was started, the time that the tractor started pulling the pickup, and the time that the data file was recorded are shown in table 3.

Table 2. Approximate target motion parameters.

Motion parameter	Approximate value
Velocity	1 ± 0.5 m/s
Acceleration	0.5 ± 0.5 m/s
Maximum angle of wheel	$15° \pm 5°$

Table 3. Description of data runs.

Filename	Description	Registration	Start time on video	Start time of tractor	Time stamp of data file
nciAf	Constant velocity	Yes	1:10	15:23	15:30
Removed trihedral from grass near the edge of the road closest to the radar. Moved trihedral on far edge of road 1 m farther downrange.					
nciAg	Constant velocity	Yes	1:00 (reset)	15:53	15:58
nciAh	Turning from far side to near side of road	Yes	8:48	16:00	16:06
nciAi	Turning from near side to far side of road	Yes	15:40	16:07	16:12
nciAj	Speed bump VHS tape broke during run	Yes	22:55	16:15	16:20
nciAk	Speed bump	Yes	29:50	16:22	16:26
ncial	Constant velocity	No	36:40	16:28	16:33
nciam	Constant acceleration, no turning	No	43:20	16:34	16:40
ncian	Turning from far side to near side of road with acceleration	No	50:10	16:42	16:47

Results

A total of nine frequency-stepped radar data files and video records were collected for various scenarios. Plots of the data were generated for file nciah. Figures 5 and 6 show plots of the bandwidth-average RCS and HRR profiles as a function of ramp number or, equivalently, time. Data of the target are plotted for ramps that were collected within the 3-dB beamwidth of the radar. Figures 5 and 6 show uncalibrated data that were not significantly different from the calibrated data. The code to generate these plots is included in the appendix.

Figure 6 shows that under certain circumstances, a mirror image of the target was formed in the HRR profiles with 10 to 15 dB of attenuation for both calibrated and uncalibrated data. This phenomenon was associated with large radar returns from the target and with a frequency response that was bell-shaped rather than flat. We are investigating his problem to determine whether it is a radar or a calibration problem.

Initial analysis of the HRR profiles indicated that the MRRR produced a modulated RCS signal that could be dynamically fit to estimate the motion of the target. The signal peak-to-trough ratio was approximately 10 dB, which is high enough to identify a half rotation of the wheel. Estimating the motion of the MRRR reflector was complicated by the lack of lateral stability of the skateboard. The MRRR had a tendency to oscillate from side to side, particularly during runs that involved turns. After the second run, the stability was improved by reducing the length of the string that attached the MRRR to the 2×4 in. board. If the target motion and measurement noise models are known, then Kalman filter techniques can be used to estimate the target position. If some of the model parameters are unknown, then techniques such as differentiated Kalman filter scoring can be applied. These techniques have not yet been applied to the data. Future tests should either use a better supporting structure, or a dihedral reflector should be mounted on the wheels of the vehicle.

Figure 5. Uncalibrated bandwidth-averaged RCS of data file nciah.

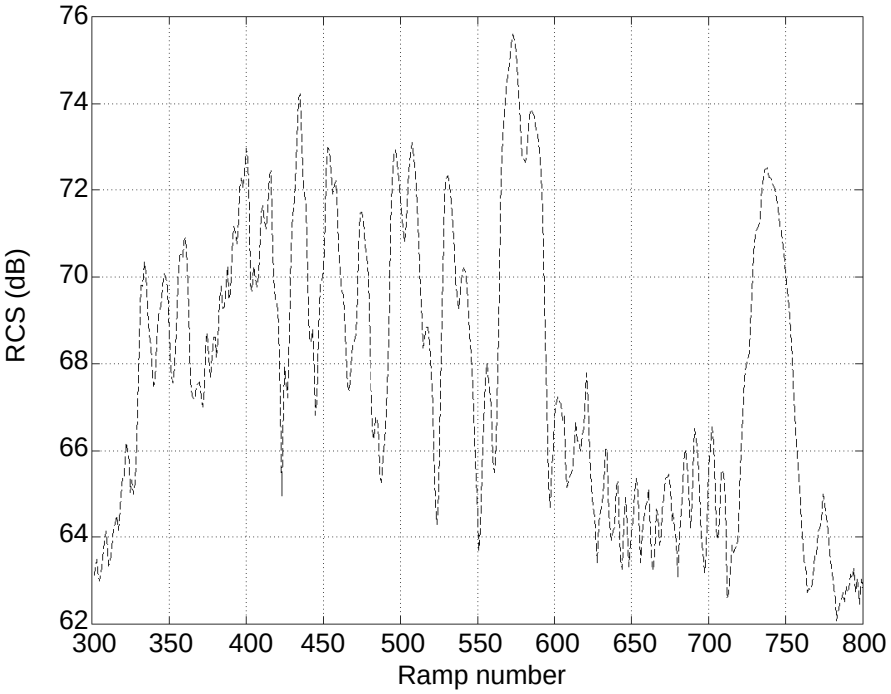
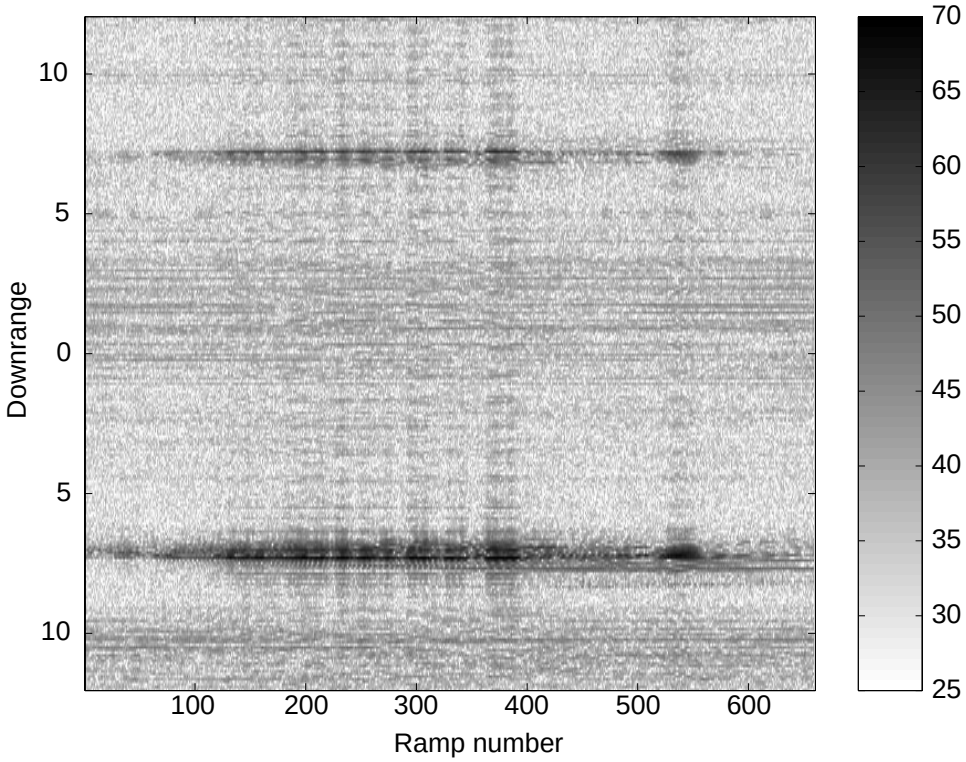


Figure 6. Uncalibrated HRR profiles of data file nciah.



Conclusions

Frequency-stepped radar data were collected on a slowly moving 1994 Chevy Cheyenne 1500 series pickup truck at K_a-band for VV polarization. Extensive radar and optical registration measurements were made. An initial analysis of the data was performed. The stationary and mobile registration reflectors were visible and sharply imaged. HRR profiles of the target looked good for most of the runs. On a few runs, false or ghost images of the target were seen in HRR profiles. This problem is being investigated.

A new MRRR reflector was designed and built to help register the radar data. The reflector modulated a radar signal that could be analyzed to estimate the target motion. However, there were lateral oscillations in the motion of the reflector that complicated the estimations of the motion of the target. Future tests should develop techniques to eliminate the problem.

Currently, ARL and the Naval Research Laboratory (NRL) are developing algorithms that can be tested using these data [5]. Testing these and other algorithms developed by industry and academia on real data should provide further insight into the development of improved ATR algorithms for weapon systems that use a real-beam radar.

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I would like to thank Suzanne R. Stratton, Robert L. Bender, and Tim Burcham of ARL, who built and maintain the instrumentation radar system and who collected the data. I also would like to thank Art Harrison and Bill Potter of ARL, who helped me construct the MRRR.

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5. G. H. Goldman and H. Dropkin, *High-Frequency Autofocus Algorithm for Noncooperative ISAR*, U.S. Army Research Laboratory, ARL-TR-1890 (May 1999).

Appendix. Visualization Software Code

```
function nci_data_report(fname,cal_flag)

% nci_data_report: quick visualization script for non-cooperative ISAR data
% collected on Sept 24, 1998, at Aberdeen Proving Ground.
% written by Jeff Goldman

if (nargin ~= 2)

  error('input: filename in single quotes, calflag 0=uncalibrated data, 1=calibrated')
end

eval(['load ' fname])

data=eval([fname]);

[num_ele,three]=size(data);

num_freq=256;

num_ramps=fix(num_ele/num_freq);

iq=zeros(num_freq,num_ramps);

times=zeros(1,num_ramps);

for ir=1:num_ramps

  times(1,ir)=data((ir-1)*num_freq +1,1);

  iq(:,ir)=data((ir-1)*num_freq +1:ir*num_freq,2) -i*data((ir-1)*num_freq +1:ir*num_freq,3);
end

if (1)  % high range resolution profiles

 hrr = fft(iq,num_freq)/(num_freq);  % hrr profiles, but use same data structure

 for iaz=1:num_ramps

   hrr(:,iaz) = fftshift(hrr(:,iaz));
 end

 hrr_power=10*log10(hrr.*conj(hrr));

 bw= 1.6e9;  % radar bandwidth

 c=3e8;  % speed of light

 figure

 dr=((1:num_freq) - num_freq/2)*c/(2*bw);
```

```
  cr=1:num_ramps;
  imagesc(hrr_power,[25,70])
  colorbar('vert')
  figure
  dr_offset=0;
  num_dr=256;
  cr_offset=200;
  num_cr=660;
  if (cal_flag==0)
    dr=((-num_dr-dr_offset:-dr_offset) + num_freq/2)*c/(2*bw);
    cr=1:num_cr;
    cs=[25,70];  % color scale in dB
    imagesc(cr,dr,hrr_power(1+dr_offset:dr_offset+num_dr,1+cr_offset:cr_offset + num_cr),cs)
    colorbar('vert')
  else
    imagesc(cr,dr,hrr_power,[-25,-5])
    colorbar('vert')
  end
  ylabel('down range')
  xlabel('ramp number')
  title(fname)
end
```

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13. ABSTRACT *(Maximum 200 words)*

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