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A Comparison and Analysis of KA-Band Radar vs. X-Band Radar

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16. Abstract

This project focuses on the New Jersey State Police commitment to highway safety by enforcing posted speed limits. Effective enforcement of speeding statutes requires measured speed to be accurate and state of the art. This requirement is necessary in order to successfully prosecute by using both moving and stationary radar. The New Jersey State Police currently utilizes MPH Industries K55 X-band radar units. The New Jersey courts have taken judicial notice as to the scientific reliability of the K55 radar. The advent of new Ka-band Radar technology now allows smaller and safer radar units to be employed. To successfully utilize these new Ka-band Radar units their speed measurement accuracy must be established in a scientific manner that will be accepted by the New Jersey courts.

This research project 1) established a program for testing the performance of the new Ka-band radar units relative to the present K55 radar, 2) monitored the implementation of this testing program, 3) reviewed the test results, 4) provided conclusions on performance and 5) documented these conclusions in a way that will facilitate the employment of Ka-band radar by the New Jersey Sate Police. The relative characteristic and performance of available laser speed detection units will also be investigated and documented.

More than 1,000 measurements proved 1) Ka-band radar speed measurements correlate very closely with the X-band measurements, 2) Weather had minimal affect on the Ka-band performance, and 3) Indicated speeds are well within National Highway Traffic Safety Administration (NHTSA) standards.

17. Key Words Traffic radar, Speed measurement, X-band, Ka-band, Doppler radar, Laser speed detection, Traffic safety		18. Distribution Statement	
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Executive Summary:

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The New Jersey State Police currently utilizes MPH Industries K55 X-band radar units. The New Jersey courts have taken judicial notice as to the scientific reliability of the K55 radar. The advent of new Ka-band Radar technology now allows smaller and safer radar units to be employed. To successfully utilize these new Ka-band Radar units their speed measurement accuracy must be established in a scientific manner that will be accepted by the New Jersey courts.

The purpose of this research project was to 1) establish a program for testing the performance of the new Ka-band radar units relative to the present K55 radar, 2) monitor the implementation of this testing program, 3) review the test results, 4) provide conclusions on performance and 5) document these conclusions in a way that will facilitate the employment of Ka-band radar by the New Jersey State Police.

The relative characteristic and performance of MPH and Stalker Ka-band radar units in comparison to the present standard K55 radar unit was determined and is documented in this report. More than 1,000 measurements prove Ka-band radar correlate closely with the X-band radar performance (mean error 0.165 mph and standard deviation 0.762 mph) and are well within National Highway Traffic Safety Administration (NHTSA) standards.

An investigation of the state of the art of laser speed detection and an evaluation of the performance of an Ultra Lyte LR B 20-20 laser speed detection unit was also undertaken as part of this project. 200 independent laser measurements were taken that compliment and substantiate earlier work in New Jersey proving the accuracy of laser speed measurements.

New and innovative programs like the introduction of the Ka-band radar speed detection devices will enable the Division of State Police to enhance their speed enforcement program to better serve the motorists who travel New Jersey's highways.

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1. Background

This project focuses on the New Jersey State Police's commitment to highway safety in enforcing posted speed limits. Effective enforcement of speeding statutes requires the methods employed to measure speed are accurate and state of the art. This requirement is necessary in order to successfully prosecute by using both moving and stationary radar. The New Jersey State Police currently utilizes MPH Industries' K55 X-band radar unit for speed measurement. This radar has been tried and tested in the New Jersey Courts. With the advent of new technology being introduced to the interior of the troop vehicles, the lack of space has become an issue that can no longer be ignored. The K55 is large and has to be mounted on the dash of the vehicle. This presents the possibility that it can become dislodged in the event of a crash, and cause injury to the occupants of the vehicle.

In 1955, the case of State of New Jersey vs. Dantonio, 115 A2d 35, 49 ALR2 d 460, the courts took judicial notice of police traffic radar operating on the Doppler Principle.

The most recent case dealing with moving radar, specifically K55, (the unit predominantly used by the Division), is State vs. Wojtkowiak 174 N.J. Super 460 (1980). The courts have taken judicial notice as to the scientific reliability of the K55 radar. This is predicated on the competent operation of the radar, after the operator has been trained in its use. (S.O.P. F-20)

The New Jersey State Police have solely used K55 as a speed detection device in the moving mode. Other stationary means of speed detection have been used, e.g., VASCAR and stop watch speed timing. Both these methods do not employ radar.

New and innovative programs like the introduction of the Ka-band radar speed detection devices will enable the Division of State Police to enhance their speed enforcement program to better serve the motorists who travel New Jersey's highways.

2. Project Objectives

The following is a list of the objective of this research project. The fifth objective was added after the start of the project. Each is discussed in this report.

1. Examine the state of the art in model development for Ka-band Radar.

2. Prove or disprove that the new technology (Ka-band Radar) is at the least as reliable as the current (X-band radar).

3. Identify data deficiencies and the statistical validity of alternative approaches.

4. Develop specifications and standards for Ka-band radar for all the requirements that are imposed by the Court system to be accepted as an instrument that measures speed.

5. Examine the state of the art in model development for laser speed detection.

3. The state of development of Ka-band Radar

A literature search was conducted to determine the state of the art in Ka-band Doppler radar technology. A bibliography generated during this search is shown in Appendix I of this report.

The two front running manufactures of Ka-band Radar units (Stalker and MPH) were contacted. Meetings were held with their representatives to discuss the operation of their Ka-band radar units and literature gathered and studied on the technical performance of there models. A sample of this material is shown in Appendix II and III. Both X and Ka-band radar units were inspected by the research team and their operation observed.

The principle features offered by the newer Ka-band radar units are their much smaller size than the older X-band models. This reduction inside is partially the result of advances in technology, but is also intrinsic in the use of a smaller wavelength that allows components to be reduce in size by a factor of approximately three. The end result allows numerous mounting options that go along with the current thoughts of minimizing the equipment in the cockpit area of the troop cars. The newest and smallest of the available units on the market offer the following list of features:

A. Computer/detachable display unit
B. Handheld remote control
C. Front antenna connection port
D. Rear antenna connection port
E. Communication port
F. Stationary/opposing direction moving operational mode software

These radars can be used as a one piece unit, or can be separated into a display unit and a computer unit. The display has windows for target, target lock and patrol. The mode window is alphanumeric and indicates the mode of operation being used - stationary, opposite direction moving and same direction moving. Indicator lights show distance, faster target, faster/slower relative speed and front/rear antenna.

- These units include ports for power, rear antenna, front antenna, and connection to speed display signs, in-car video, personal computers, and a hand held remote control.

- All of the Ka-band units are state of the art and extremely small in comparison to the X-band MPH Industries, K55 units presently in use by the New Jersey State Police.

- These units have the capability to be connected to the Mobile Video Recorders in troop cars, or possibly to the Mobile Data Computers, which meets the goal of downsizing the equipment in the cockpit area of the troop car.

- If the Ka-band units are used in their present design, the read out display can be detached from the computer and mounted in any manner that would benefit the operator and front seat passenger of the troop car. The computer unit can be mounted under the seat or in the glove compartment. The end result is the same no matter where or how this unit is mounted.

The newer radar units also employ digital signal processing (DSP). This technology is applicable to both their X and Ka-band products. It allows them to differentiate between multiple targets based on spectral analysis of the received vehicular velocities, and should be of significant value in the application of their Ka-band radar units – see Appendix III.

4. Prove/disprove Ka-band Radar is as reliable as X-band radar

To evaluate the performance of Ka-band traffic radar, the most technologically advanced available units from the two leading traffic radar manufactures were selected for field testing. The Ka-band radars chosen were the DSR 2X made by Stalker and the BEE-III made by MPH. Tests were conducted in a variety of locations with actual road traffic under fair, rain and snow weather conditions. Tests were conducted during both stationary and moving measurement of speed.

The test documentation plan and measurement procedure was reviewed by the project team. An MPH K55 X-band radar presently used by the New Jersey State Police and accepted as a standard by the New Jersey courts was mounted side-by-side with the unit under test in a standard troop car reserved for the project. Speed readings from both radars were recorded along with information on test conditions as weather, measured vehicle type, etc. A sample form used for recording test results is shown in Appendix IV. Pictures of the vehicle used for testing and the positioning of the radar units are shown in Appendix V.

1,100 documented measurements were made over an approximately 10 month period that compared the performance of a Ka-band radar unit to the reference MPH K55 X-band radar unit. Of particular concern was the affects of weather on Ka-band vs. X-band Doppler radar performance. A total of 600 measurements were made during clear/sunny conditions, 400 were made in rain/cloudy-wet conditions and 100 during snow. The testing was divided up between the radar maker's units and ended with 500 measurements with the Stalker radar and 600 with the MPH radar. 200 measurements were made while moving and the remainder stationary. The different types of measurements are documented in Table I.

TABLE I   DISTRIBUTION OF MEASURMENTS BY Ka-BAND RADAR UNIT TYPE AND CONDITION

CONDITION	TOTAL MEAS.	DSR 2X MEAS.	BEE-III MEAS.
CLEAR/SUNNY	600	200	400
RAIN/ WET	400	200	200
SNOW	100	100	*
MOVING	200	100	100

* No measurements were taken with the MPH BEE-III radar unit in snow.

These results clearly show that the speed measurements at Ka-band correlate closely with the X-band radar measurements (< 3 mph error in virtually all cases) as discussed further in the next section. They are well within National Highway Traffic Safety Administration (NHTSA) standards for both the MPH and Stalker radar units.

5. Statistically validate radar testing approaches

The results of the comparative testing between Ka-band to X-band radar units were consolidated and statistically analyzed. The results of this analysis is summarized in Table II and shown in the following figures.

TABLE II SUMMARY OF THE TEST MEAN SPEED DIFFERENCES
AND STANDARD DEVIATIONS

MEASUREMENT CLASSIFCATION	MEAN SPEED DIFFERENCE (mph)	STANDARD DEVIATION (mph)
ALL Ka-BAND MEASUREMENTS	0.165	0.762
SUNNY/CLEAR (ALL UNITS)	0.129	0.518
RAIN/CLOUDY-WET/ SNOW	0.210	0.943
SNOW (ONLY)	0.450	0.671
MOVING (ONLY)	0.157	1.114
STALKER (ALL)	0.240	0.736
MPH (ALL)	0.103	0.743

Figure 1 shows the probability density (PD) of the speed difference between the reference K55 X-band radar unit and the results obtained for both the Stalker DSR 2X and MPH BEE-III Ka-band radar units under all weather conditions and includes both stationary and moving data. It can be seen that the agreement is excellent. The mean speed error is less than 0.165 mph. The standard deviation is less than 1 mph (0.762 mph). Traffic radar units are to be accurate within ± 3 mph. Virtually no errors outside of this range were indicated. The chance of a measurement error greater than 3 mph was 0.036 percent.

Fig. 1 - PD of Ka and X-band radar speed difference for all conditions and units
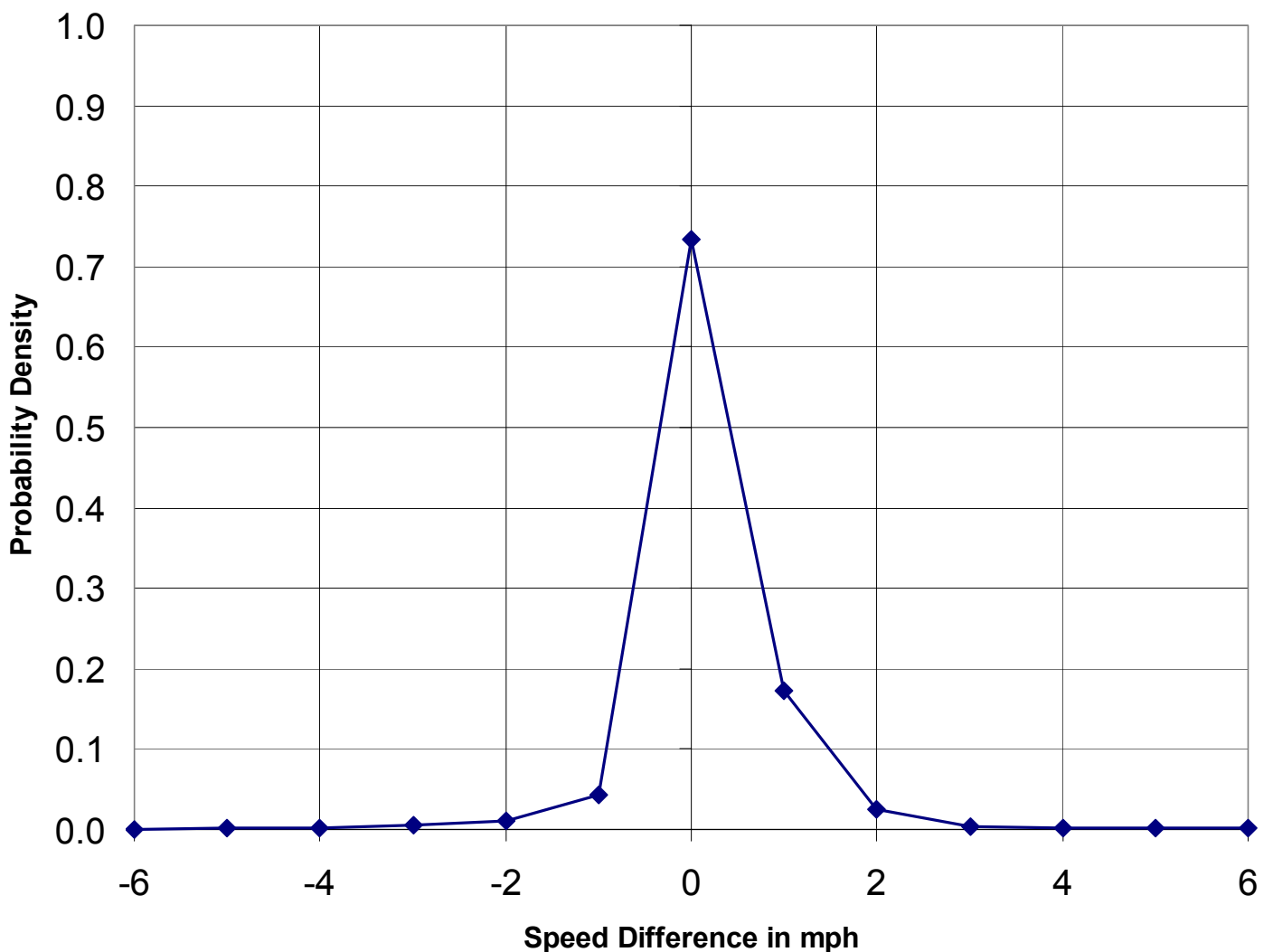
Figure 2 shows the PD of the speed difference between the reference K55 X-band radar unit and the results obtained for both the Stalker DSR 2X and MPH BEE-III Ka-band radar units during just fair weather conditions. Both stationary and moving data is included. There is little difference between this figure and Figure 1, (mean speed error of 0.128 mph and standard deviation of 0.518 mph), which indicates that weather conditions have minimal affect on Ka-band measurements.

Fig. 2 - PD of Ka and X-band radar speed difference for sunny/clear weather
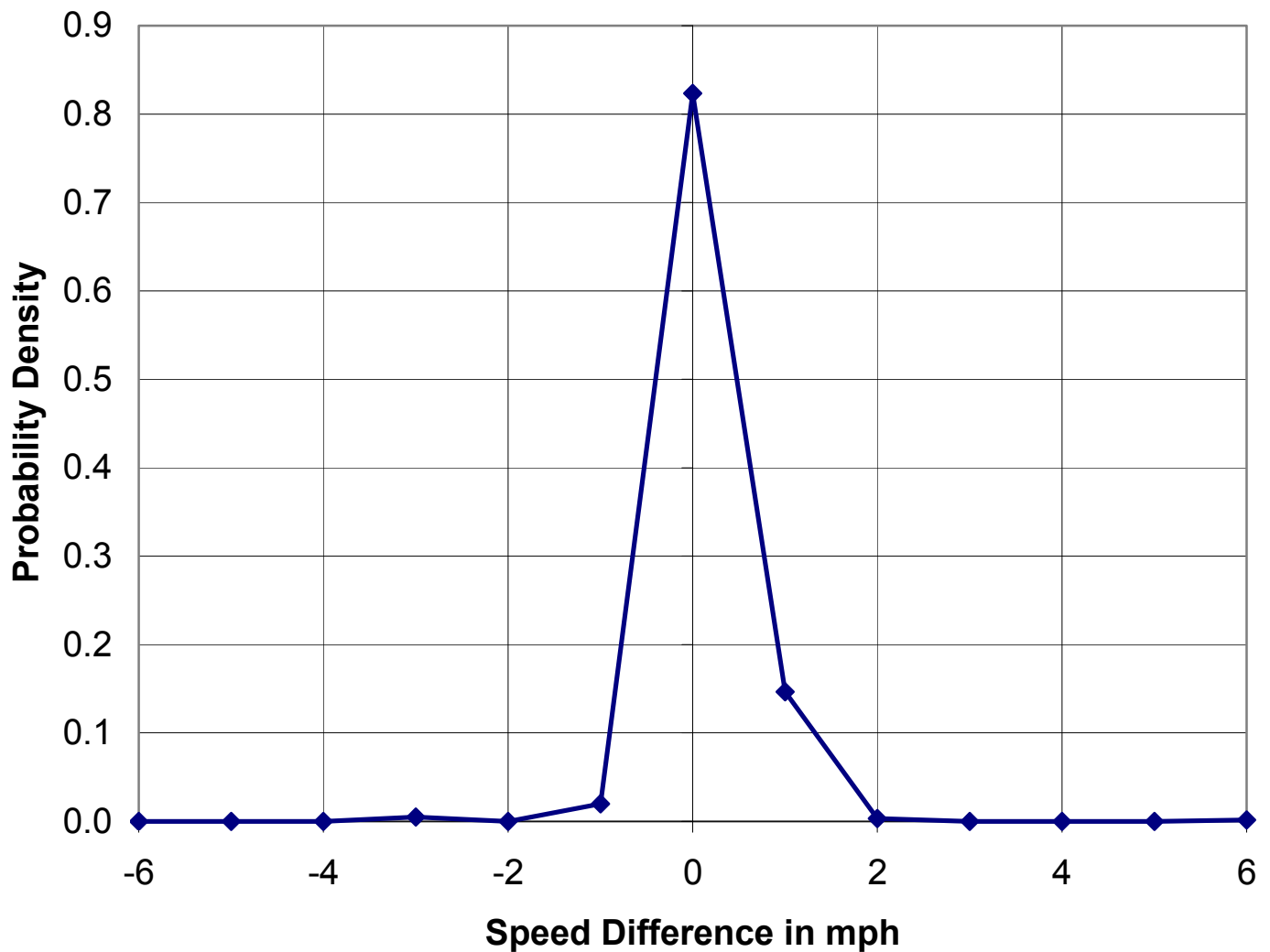
The next graph, Figure 3, shows the PD of the speed difference between the reference X-band and Ka-band radar units for bad (rain/cloudy-wet and snow) weather conditions. Again both the Stalker DSR 2X and MPH BEE-III radar measurements have been combined, and measurements taken while moving have been included. Although slightly less accurate than for all weather, there is still excellent correlation between the X and Ka-band measurements. The mean error is only 0.210 mph and the standard deviation is still less than 1 mph (0.943 vs. 0.769 mph). The accuracy is well within the required $\pm$ 3 mph with virtually no errors greater than 2 mph observed. The chance of a measurement error greater than 3 mph was 0.060 percent.

**Fig. 3 - PD of Ka and X-band speed difference for bad weather (rain, cloudy/wet and snow)**

Probability Density

Speed Difference in mph
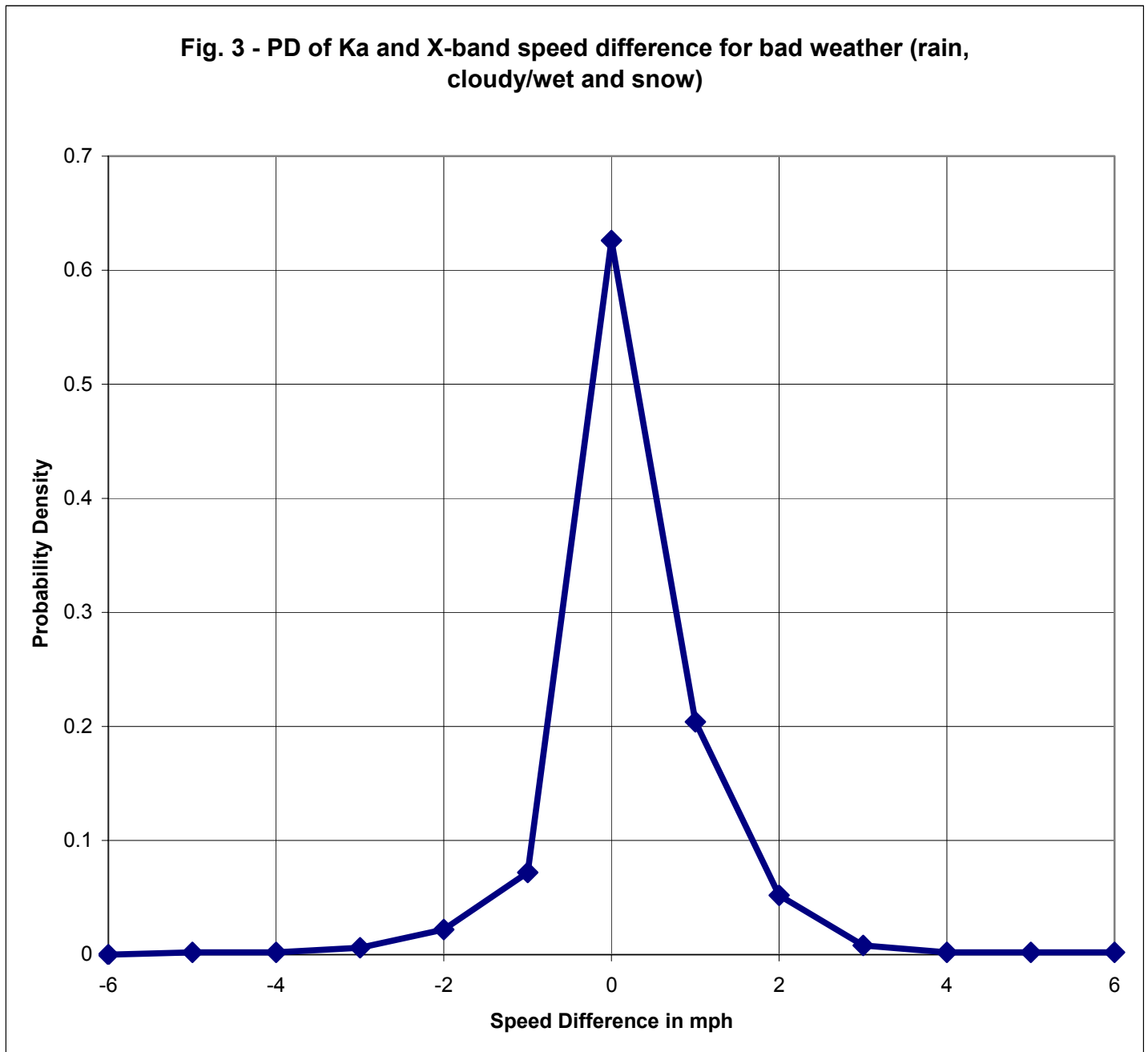
Figure 4 shows the effect of only snow on the PD of the speed difference between the reference X-band and Ka-band radar unit measurements. These results are based on only comparison with the Stalker DSR 2X Ka-band measurements as there was no opportunity to get additional measurements in snow with the MPH BEE-III radar unit. The fact that this data was taken only with the Stalker DSR 2X Ka-band unit should not bias these results as shown by later comparisons between these radars. Both units offer very comparable performance. The performance in snow was actually better than the overall bad weather results (mean speed error of 0.450 mph and standard deviation of 0.671 mph). Based on the accumulated data, Dr. Guida sees no significant degradation at Ka-band in performance under different weather conditions.

Fig. 4 - PD of Ka and X-band speed difference for snow conditions
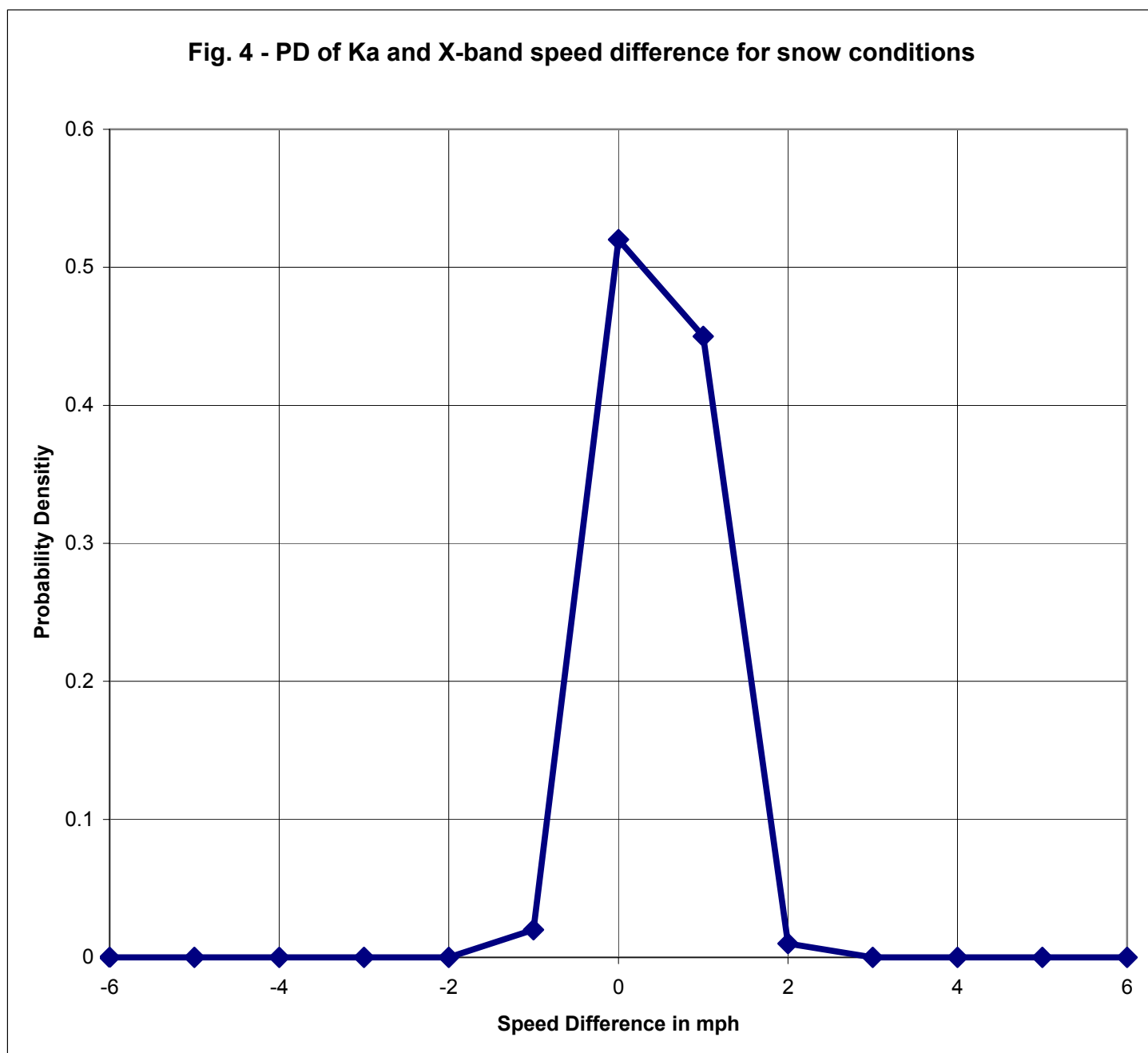
Figure 5 shows a comparison of the measured performance (speed difference) of the Ka-band Stalker DSR 2X and MPH BEE-III radar units to the X-band K55 reference radar unit under all test conditions (except snow). Both units are comparable and performed well within the specified measurement uncertainty. Although to the eye the errors of the MPH may appear slightly smaller, the difference in standard deviations is only 0.013 mph, (0.743 vs. 0.736 mph), which is insignificant. The difference in the graph is most likely due to a very small calibration error (mean error of 0.103 vs. 0.240) that cannot be totally eliminated in practice.

Fig. 5 - PD of speed difference between reference X-band K55 radar and the Stalker DSR 2X and MPH BEE-III Units
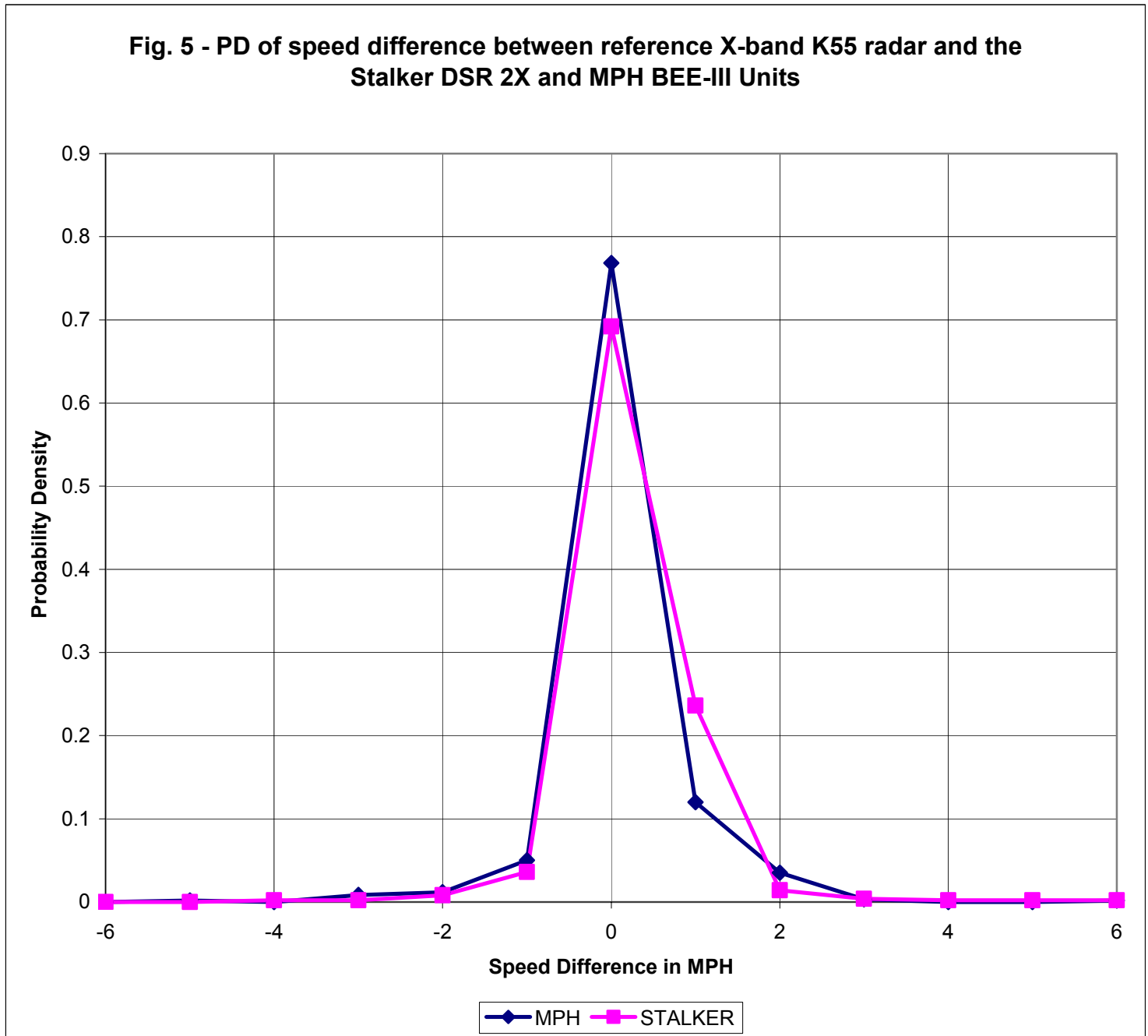
Figure 6 shows the results of the speed difference measurements taken while in motion. Both the Stalker DSR 2X and the MPH BEE-III Ka-band radar unit results are combined. These results include measurements taken during both clear and rainy weather conditions. Although these measurements show greater variance than stationary results, (standard deviation of 1.114 vs. 0.762 mph), there is still excellent correlation between the X and Ka-band measurements. The mean speed error is only 0.157 mph and the accuracy is still well within ± 3 mph with negligible errors greater than 2 mph observed. The chance of a measurement error greater than 3 mph was 0.067 percent. This figure is essentially the same as for the *bad weather* conditions.

FIG. 6 - PD of Ka and X-band speed difference for measurements taken from a moving vehicle
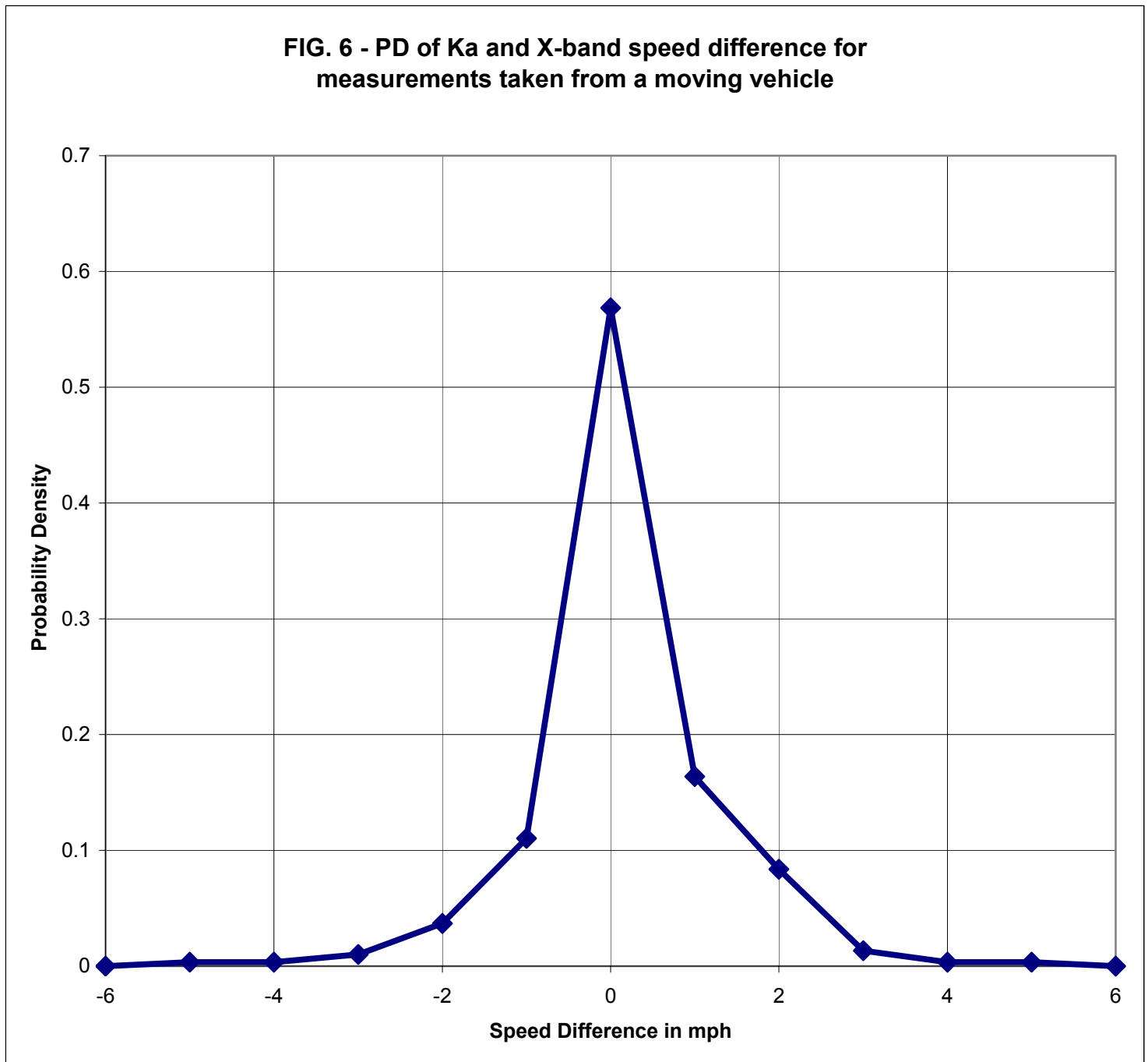
6. Develop specifications for Ka-band radar meeting court system requirements

Sample specifications for Ka-band traffic radar is shown in Appendix II. It is clear from the statistical results that both types of Ka-band radar will more than meet the accuracy requirements imposed by the law and NHTSA standards. The relative technical and operational merits of the Stalker and MPH Ka-band radar units have been reviewed. It was agreed that there are no significant differences between the measured performances of both units. All units performed well with in the specified measurement uncertainty. The Stalker radar offers the advantage of simultaneously displaying the speed of vehicles located both in front and in back of a patrol car. The MPH radar displays either, but requires the operator to manually switch the display from one direction to the other. The MPH is slightly smaller in size.

The real issue to be addressed in this part of the study was to ensure that the testing supporting the specifications will be accepted by the New Jersey Court system. To achieve this objective the State's Attorney General's office was consulted. Minutes of a meeting held with Deputy Attorney General Dell' Aquilo, representing the Attorney General's Office, are attached in Appendix VI. This meeting confirmed that the K55 X-band radar is the legal standard in New Jersey, and that comparing all measurements to this radar was appropriate and would be an effective way of substantiating the study's results in court. He provided a copy of a 1998 New Jersey Superior Court Proceedings dealing with the validity of Laser Speed Detection. This documented was studied and used as a reference for presenting the results in this report. Deputy Attorney General Dell' Aquilo commended the use of a group that is independent of the State to conduct the study and felt that the use of real traffic conditions added to the study's credibility.

Deputy Attorney General Dell' Aquilo also suggested that the publication of the results of the study was another way of increasing the report's credibility and validating the results. Dr. Katz is submitting a paper on the study's results to the IEEE 2008 Sarnoff Symposium.

7. Examine the state of development for Laser Speed Detection

The scope of the laser study was narrower than Ka-band radar evaluation, but a similar approach was followed. A search of laser based speed detection literature was first conducted. The results of this search are shown in Appendix VII. The manufactures of laser speed detection equipment were also contacted. Because the State Police already has some experience with laser speed detection using an Ultra Lyte LR B 20-20, this unit was selected for testing. In all cases the speed indicated by the Ultra Lyte LR B 20-20 was compared to the reference X-band MPH K55 radar unit. Tests were conducted in several locations with actual road traffic. Since laser measurements are normally only taken from a stationary location outside of the vehicle (measurements can be taken from inside through an open window), measurements were made primarily under fair weather conditions although some measurements were made with a cloudy sky. A total of 200 measurements were taken, but it was found that some learning is required to take accurate laser speed detection measurements. The operator must make certain that the laser unit is pointed at the same vehicle as the X-band radar is responding to. Because of the need for learning time by the operator, the first set of 40 laser based measurements were excluded and only the latter 160 measurements were used in the statistical analysis. All measurements taken after the initial *learning* session were included in the study. Figure 7 shows the results of laser speed detection testing. These results are comparable to the Ka-band radar measurements and show excellent correlation with the reference MPH K55 X-band radar. The mean speed difference was only -0.125 mph and the standard deviation 0.748 mph, which is almost

identical to the overall Ka-band results (0.762 mph). The accuracy is well within ± 3 mph requirement with almost no errors greater than 1 mph observed.

Figure 8 shows a laser speed detection test in progress. Two persons are required to perform this test. One located outside the car with the laser unit, which as noted must be normally operated outside of the car, and a second person to read the X-band radar inside the car. The measurements must be synchronized to insure that the same vehicle is being measured by both units.
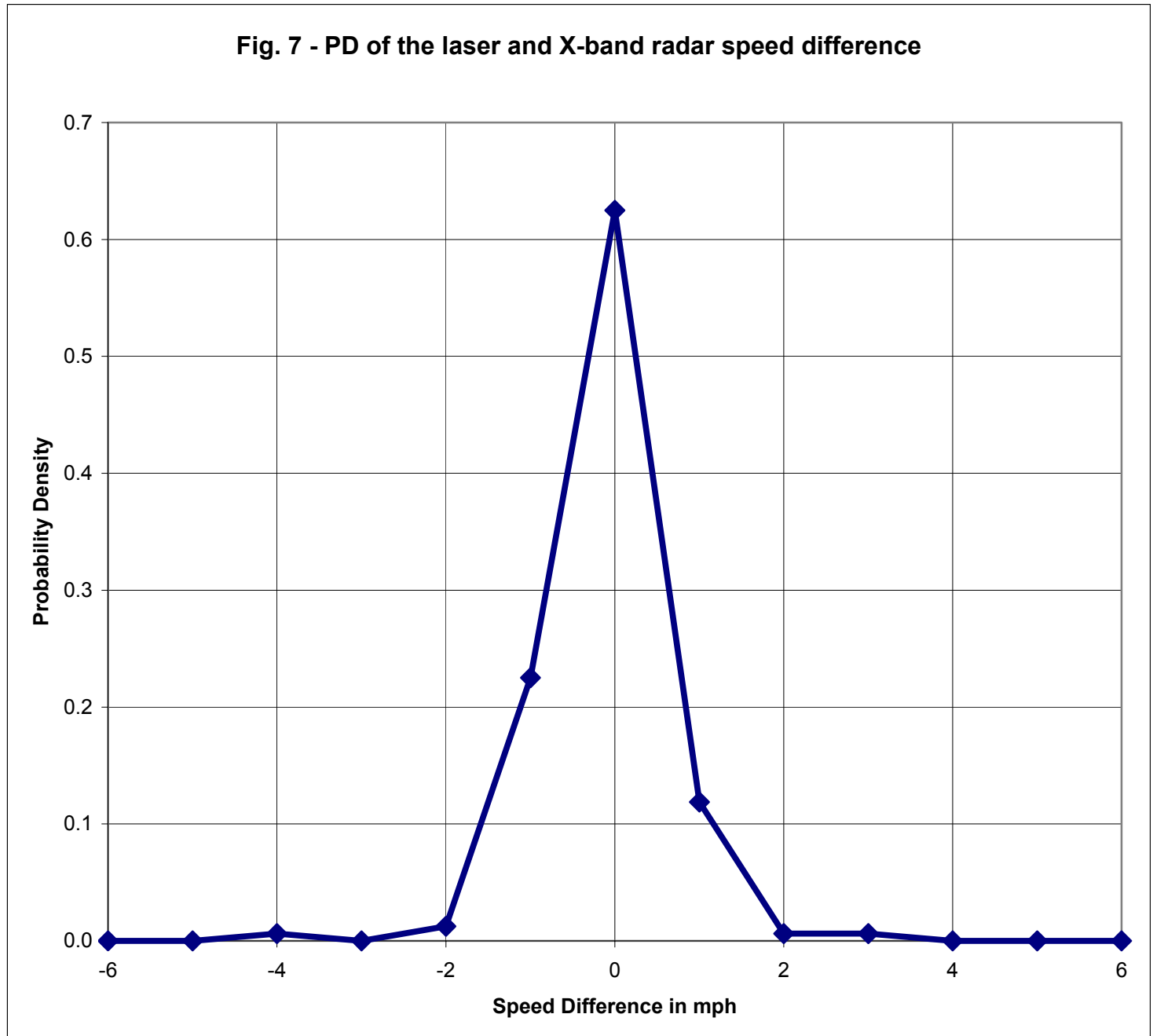

Fig. 7 - PD of the laser and X-band radar speed difference

Figure 8. TCNJ student research assistant Steve Mach taking a laser measurement.

8. Conclusion

All objectives of this study have been completed.

The state of development of Ka-band traffic radars has been researched. The two front running Ka-band traffic radar units made by MPH and Stalker were thoroughly studied and evaluated. Literature on the technical performance of these and other models was gathered and reviewed.

Both Ka-band traffic radars unit investigated were shown to be as reliable and accurate as the present X-band standard. More than 1,000 measurements in all types of weather, with actual highway traffic were taken and prove that the measurements at Ka-band are comparable with the X-band radar measurements and are well with in NHTSA standards.

The measurements were statistically analyzed and graphically illustrated to demonstrate the excellent performance of available Ka-band radar units. The standard deviation between the Ka and X-band radar units was less than +/- 0.762 mph.

A list of specifications and complimentary data to prove the accuracy and reliability of Ka-band radar measurements is included in this report in a format that will meet the needs of the New Jersey Court System, the State Attorney General's Office and the State Police.

The state of development for laser speed detection was also examined. 200 independent laser measurements were taken that compliment and substantiate earlier work in New Jersey and prove the accuracy of speed laser measurements.

This work was completed on schedule and in budget. A financial summary is included in Appendix IIX of the report.

Appendix I Doppler Speed Radar Literature Search

1. Boric-Lubecke, O.; Lubecke, V.M.; Host-Madsen, A.; Samardzija, D.; Cheung, K., **Doppler radar sensing of multiple subjects in single and multiple antenna systems,** Telecommunications in Modern Satellite, Cable and Broadcasting Services, 2005. 7th International Conference on, Volume: 1 28-30 Sept. 2005, Page(s): 7- 11 vol. 1.

Summary: Doppler radar life sensing has shown promise in medical and security applications, however the problems of motion artifacts and presence of multiple subjects limit the usefulness of this technique.

2. Ciuciu, P.; Idier, M., **Regularized Doppler radar imaging for target identification in atmospheric clutter,** Acoustics, Speech, and Signal Processing, 2004. Proceedings. (ICASSP '04). IEEE International Conference on
Volume: 5 17-21 May 2004, Page(s): V- 265-8 vol.5.

Summary: We develop a method for the formation of Doppler radar images with enhanced features. This problem, when studied as an adaptive spectral estimation problem, is particularly ill-posed because of the small number of data. Our approach is based on a re

3. Fisher, P.D., **Improving on police radar,** Spectrum, IEEE, Volume: 29 Issue: 7 Jul 1992, Page(s): 38-43.

Summary: The use of lasers, cameras, and advanced signal processing to help isolate individual offenders on crowded highways is discussed. The limitations of the predominant radar in use today, namely down-the-road Doppler-radar.

4. Fisher, P.D.; Pyhtila, J.W., **Timing quantization error in lidar speed-measurement devices,** *Vehicular Technology, IEEE Transactions on,* page(s): 276-280, Volume: 49, Issue: 1, Jan 2000.

5. Greneker, G., **Millimeter wave safety warning system for in-vehicle signing,** Radar Conference, 1997., IEEE National, 13-15 May 1997, Page(s): 182-185.

Summary: Georgia Tech Research Institute (GTRI) has developed a millimeter wave safety warning system for in vehicle signing that is soon to be tested for applicability for use in the nation's Intelligent Transportation System (ITS) (formerly IVHS).

6. Heide, P.; Magori, V.; Schwarte, R, **Coded 24 GHz Doppler radar sensors: a new approach to high-precision vehicle position and ground-speed sensing in railway and automobile applications,** Microwave Symposium Digest, 1995., IEEE MTT-S International, 16-20 May 1995, Page(s): 965-968 vol.2.
Summary: Coded 24 GHz Doppler sensors have been realized to perform high-precision non-contact vehicle position and speed measurements. Encoding the radar signal with a spread-spectrum code is the key to a significantly enhanced sensitivity combined with a radar.

7. Kleinhempel, W.; Bergmann, D.; Stammler, W., **Speed measure of vehicles with on-board Doppler radar,** Radar 92. International Conference, 12-13 Oct 1992, Page(s): 284-287.

Summary: The system configuration of an on-board Doppler radar system is presented which is based on millimeter wave frontends (61 GHz) and digital processing of baseband signals. For the estimation of the Doppler frequency a novel method is used

8. Klugmann, D.; Stephan, R., **Calibration of portable FM-CW Doppler radar profilers with an artificial target,**
Geoscience and Remote Sensing Symposium, 2004. IGARSS '04. Proceedings. 2004 IEEE International
Volume: 6 20-24 Sept. 2004, Page(s): 3953- 3955 vol.6.

Summary: Two portable mono-static FM-CW Doppler radar profiler systems have been calibrated using a continuously rotating corner reflector. The front-ends of both radars apply semiconductors for the generation of the transmitted power.

9. Leeson, D.B.; Johnson, G.F., **Short-term stability for a Doppler radar: Requirements, measurements, and techniques,** Proceedings of the IEEE Volume: 54 Issue: 2 Feb. 1966, Page(s): 244- 248.

Summary: Short-term frequency stability is an important parameter affecting resolution and range of a Doppler radar. This paper describes system and circuit requirements found in a typical airborne Doppler radar designed for operation in a severe vibration.

10. Rahman, Z.A.; Hasan, W.S.W.; Noor, S.B.M.; Hassan, M.K., **Speed trap detection with Doppler effect,**
Research and Development, 2003. SCORED 2003. Proceedings. Student Conference on 25-26 Aug. 2003, Page(s): 202- 206.

Summary: In this paper, the 8-bit MC68HC11 MCU micro controller is used to receive data speed from Doppler radar speed sensor. Vehicle speeds are detected by Doppler radar speed sensor and then sent to a micro controller.

11. Rasshofer, R.H.; Biebl, E.M., **A direction sensitive, integrated, low cost Doppler radar sensor for automotive applications,** Microwave Symposium Digest, 1998 IEEE MTT-S International, Volume: 2 7-12 Jun 1998, Page(s): 1055-1058 vol.2.

Summary: We fabricated and tested an integrated, low cost, W-band Doppler radar sensor, capable to provide direction sensitive velocity information. The front-end consists of an active integrated antenna in self-mixing operation and a surface-wave coupled, microstrip.

12. Roselli, L.; Alimenti, F.; Comez, M.; Palazzari, V.; Placentino, F.; Porzi, N.; Scarponi, A., **A cost driven 24 GHz Doppler radar sensor development for automotive applications,** Radar Conference, 2005. EURAD 2005. European, 6-7 Oct. 2005, Page(s): 335- 338.

Summary: This paper deals with a low-cost 24 GHz Doppler radar sensor for traffic surveillance. The basic building blocks of the transmit/receive chain, namely the antennas, the balanced power amplifier (PA), the dielectric resonator oscillator (DRO).

13. Westphal, R.; Kessler, A., **35-GHz-Doppler radar for law enforcement agencies in Europe,** Microwave Symposium Digest, 1988., IEEE MTT-S International, 25-27 May 1988, Page(s): 1031-1033 vol.2.

Summary: An experimental program was conducted to investigate the reflectivity of moving motor vehicles using a Ka-band CW Doppler radar, as well as the accuracy of speed measurements as a function of parameters such as antenna polarization, beam ill.

14. Woll, J.D., **Monopulse Doppler radar for vehicle applications,** Intelligent Vehicles '95 Symposium., Proceedings of the, 25-26 Sep 1995, Page(s): 42-47.

Summary: This paper describes an efficient, forward looking, radar system that can be used for vehicle applications including collision warning, collision avoidance and adaptive or intelligent cruise control. A Doppler radar system is described.

Appendix II Sample Specifications for Ka-band Traffic Radar

This specification describes a state-of-the-art, directional Ka-band traffic radar with two antennas. The radar shall measure vehicle speeds from a stationary or moving patrol vehicle. The radar shall be capable of measuring the speed of vehicles moving in the same direction as the patrol vehicle while the patrol vehicle is moving, and it shall be equipped with a *fastest vehicle mode*. When measuring same direction speeds, the radar shall require no input from the officer in order to accurately calculate the target speeds. The radar shall also have a mode that measures speeds while at the same time evading radar detectors. The radar shall conform to all NHTSA specifications, and it shall be listed on the most recent International Association of Chiefs of Police's Consumer Products List.

1. System Description

1.1 The radar system shall consist of a separable display/counting unit, remote control unit, two Ka-band antennas, and all necessary cables and brackets necessary for installing the system in a patrol vehicle.

1.2 The display unit shall house all of the speed displays and status indicators for the radar system. No connectors will be present on the front panel of the display unit. It shall connect to the counting unit via a single connector. The display unit shall be 1.5" tall by 5" wide by 1.5" deep or smaller.

1.3 The counting unit will contain the speed processing hardware for the radar. It shall be no larger than 1.5" tall by 5" wide by 2" deep. It shall connect to the display unit with via a single cable. It shall have receptacles on its rear for connecting two antennas, and an interface for connecting to other equipment.

1.4 The remote control shall be part of the system and communicate to the rest of the system wirelessly. The remote control shall be easily operated while the operator is driving.

1.5 The radar shall be able to measure speeds in all of the standard radar modes: stationary, opposite direction moving, and same direction moving. In addition, the radar shall have a stopwatch mode.

1.6 The radar shall employ directional radar technology. No input from the officer shall be necessary for the radar to accurately measure vehicle speeds in same direction moving mode. In addition, in stationary mode, the radar shall be able to measure the vehicle in a selected direction while completely ignoring the traffic moving in the opposite direction. The range of the radar shall not be affected by opposite direction targets. A mode shall be present in which the radar shall measure the speed of the strongest target moving in either direction; in this mode, the radar shall indicate the measured target's direction in its mode window.

1.7 The radar shall include a mode of operation that allows the operator to measure the speed of targets using the microwave radar beam without setting off any radar detectors. In this mode, the radar, upon command from the operator, shall transmit short, computer-controlled radar bursts in order to measure target speeds. The duration of this pulse must be short enough so that radar detectors are not alerted. This mode of operation must be in addition to the traditional Standby or RF Hold mode of the radar.

1.8 The radar shall be upgradeable for adding or removing features in the field. (Radars which require return to the manufacturer for upgrade are not as desirable).

1.9 The radar shall provide a Doppler audio signal to the operator. In moving mode, the Doppler audio signal shall correspond to the closing speed of the target vehicle. In directional stationary mode, the audio shall correspond to the operator for the target being measured, and audio signals generated by vehicles moving on the opposite direction (the direction not selected for monitoring) shall be suppressed.

1.10 A speedometer interface, including all necessary adapters and cables shall be supplied with the radar unit.

2. System specifications

2.1 The radar unit shall operate at a nominal 13.6 Vdc and be fully operational from 10.8 Vdc to 16.5 Vdc (battery voltage +/- 20%).

2.2 Operating current shall never exceed 2 Amps.

2.3 The radar unit shall operate from -30 °C (-22 °F) to 60 °C (140 °F).

2.4 The radar unit shall operate up to 90% relative humidity @ 37 °C (99 °F).

2.5 The audio shall increase in volume as the target vehicle approaches the antenna and increase in pitch with an increase in closing speed.

2.6 The counting unit shall employ DSP technology.

2.7 All indicators and displays shall automatically adjust their brightness for optimal day/night viewing.

2.8 The radar unit shall use standard connectors to communicate with external devices such as a large display, a remote display, or camera system. The protocol transmitted through the data port shall be a format accepted by at least five different manufacturers of in-car video equipment so that the agency will not be locked into a single brand or group of brands. The manufacturer must include a copy of their data protocol and a list of compatible video systems to the agency upon request.

2.9 Since there is no established case law for fastest mode, this mode shall operate on a momentary basis, and the radar shall be incapable of locking fastest mode speeds. A unit which displaces the strongest target's speed with the fastest vehicle's speed or allows the speed of the fastest vehicle to be locked in is not acceptable. Fastest mode shall be disabled when the radar is operating in same direction moving mode.

3. System Indicators

3.1 When the operating voltage is below 10.8 Vdc, the radar unit shall display no active speed readings and shall indicate the low voltage condition.

3.2 The radar unit shall employ radio frequency detection circuitry and the presence of such interference shall be indicated. The radar unit shall not display any active speed indication when interference is present.

3.3 The radar unit shall indicate the currently active antenna. The operator must be able to tell if the radar is in standby or if it is transmitting, which antenna is currently selected, and the direction of the target vehicle.

3.4 The indication of the radar mode must be retained after a speed has been locked in and the unit placed in standby. The radar unit shall indicate the antenna on which a target was locked and the targets direction of motion.

3.5 The radar unit shall indicate the activation of fastest mode.

3.6 The radar unit shall indicate when it is operating in the same direction moving mode.

3.7 The radar unit shall indicate stationary mode operation.

4. Speed indicators.

4.1 The radar unit shall provide a dedicated patrol speed numeric display. In standby mode, this display shall display the patrol speed at the time of target locking.

4.2 The radar unit shall provide a dedicated strongest target speed numeric display. Under no circumstances shall any target other than the strongest be presented in this display

4.3 The radar unit shall provide a locked target display. This display may be used for other temporary modes such as to display fastest targets or to indicate selection of a slow target during same direction operation.

4.4 The radar shall only lock the speed of the strongest target. If the lock button is pressed while the radar is in fastest vehicle mode, the radar shall lock the speed of the strongest target.

4.5 In stationary mode, the radar unit shall display target speeds from <= 15 mph (24 kph) to >= 200 mph (321 kph).

4.6 In opposite direction moving mode, the radar unit shall display patrol speeds from <= 12 mph (19 kph) to >= 120 mph (192) kph.

4.7 In opposite direction moving mode, the radar unit shall display target speeds from >= 15 mph (32 kph) to a closing speed of >= 120 mph (192 kph).

4.8 In same direction moving mode, the radar unit shall display patrol speeds from <= 20 mph (40 kph) to >= 120 mph (192 kph).

4.9 In same direction moving mode, the radar unit shall display target speeds of +/- 70% of the patrol speed. Target speed must be a minimum of 3 mph (5 kph) greater or lesser than the patrol speed in order to be displayed.

5. Display Unit Controls

5.1 Only one control shall be present on the display unit. It shall have a push button switch for power on/off.

6. Antenna

6.1 The radar antenna shall operate on the standard radar frequency of 33.800 +/- 0.100 GHz (Ka band).

6.2 The antenna output power shall not exceed 50 milliwatts.

6.3 The antenna's radiated power density shall not exceed 2 mW/cm 2 at 5 cm.

64 The antenna shall be type-accepted in compliance with FCC Part 90.

6.5 The radar beam shall be circularly polarized, and the beam width between the half power points shall not be less that 13 degrees and shall not exceed 15 degrees.

6.6 The antenna shall be completely weatherproof, able to be mounted indefinitely outside of the patrol vehicle.

The Most Significant Advance in Radar Technology Since DSP

Same Lane Problems Eliminated

Conventional radars force the operator to visually estimate and manually input faster or slower targets each time in order to calculate readings. The DSR automates the procedure, making same lane operation as accurate and simple to use as opposite mode operation.

NOW AVAILABLE. Same lane fast display and same lane fast lock. The operator can now DISPLAY or LOCK:
1) Strong targets
2) Fast targets
WHILE IN:
1) Same lane mode
2) Opposite lane mode
3) Stationary mode

The Revolutionary Stalker DSR

Same Lane 'Faster' Target Locking Is Another STALKER First

Now, an operator has a choice of locking either the same lane faster target or the same lane stronger target. In fact, same-lane faster target display and locking is a Stalker exclusive.

Dramatically Simplifies Moving "Same Lane" Operation While Automatically Ensuring Accuracy

With direction sensing capabilities, the DSR is able to automatically determine if vehicles in the same lane are closing or going away from the radar. This allows the DSR to automatically measure same lane traffic speeds as simply and accurately as it does for oncoming traffic. No longer does the operator need to tell the radar if same lane traffic is closing or going away from the patrol vehicle. The Stalker DSR is the first radar to make same lane operation simple, accurate, and automatic.

A Giant Leap in the Effectiveness of Stationary Operation

The Direction Sensing ability of the Stalker DSR allows the operator to select a specific direction of traffic to monitor. The DSR can measure closing targets while automatically ignoring vehicles that are going away - even if the target moving away is closer than a distant closing target. Imagine the typical situation where you wish to measure closing vehicles at a lengthy distance on a two-lane road. Just when a distant car enters the picture, a truck passes by your location heading away from you (and towards the approaching car). A conventional radar would be forced to display the truck's speed until it is out of the area - and you could not measure the closing car's speed. The DSR is able to completely ignore the truck because it is traveling <u>away</u> from the radar, thereby being able to clock the <u>closing</u> vehicle - even though it is still distant. The Stalker DSR makes stationary operation very useful and highly effective in all locations.
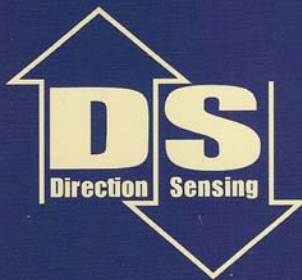
Provides Voice Verification of the Location, Radar Mode, and Direction

Whenever a target is locked, the Stalker DSR audibly tells the operator WHICH antenna was used (front or rear), what MODE the radar is operating in (moving or stationary), and the DIRECTION (opposite or same direction) the vehicle was traveling. This added step assists the operator in ensuring accuracy every time.

28

The Smallest Detachable Display Unit

True Doppler Audio

The audio Doppler tone in opposite mode operation is generated from the target's actual speed (not closure speed) so the tone always correlates directly to the target's speed - regardless of patrol speed. In moving mode, audio tones from conventional radars are based on closure rate, so the patrol speed changes the pitch of the audio tone. With Stalker's industry exclusive true Doppler audio, operators can always associate tone pitch with target speed, which eliminates the need to constantly watch the display to determine target speed.

Vehicle Speed Sensing (VSS) Operation Is Standard

When the VSS cables, supplied as standard equipment, are installed, the DSR automatically self-calibrates and then provides perfect patrol speed tracking. In addition, it automatically switches between moving and stationary modes when the vehicle starts and stops.
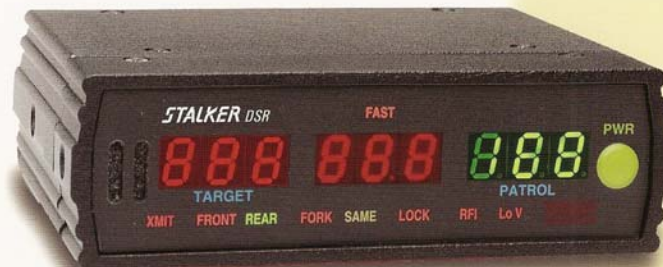
Small Display / Counting Unit

The small display and counting unit is compact enough to be mounted almost anywhere. Having such a small display reduces dashboard visibility problems and eliminates interference with airbags.

Read-Thru Lock, With 3 Window Multi-Colored LEDs

The Stalker DSR utilizes three colors (red, amber, and green) to differentiate between the strongest, faster, and patrol speeds.

Detachable Display Unit

If an even smaller unit is desired, the display / counting unit can be separated easily by loosening 2 screws. The display can then be mounted separately using an interconnect cable.

Strongest and Faster Targets Simultaneously Displayed (and/or Locked) in Separate Display Windows.

Strongest **Faster** **Patrol**

By displaying both strongest and faster targets simultaneously, the Stalker DSR can monitor faster vehicles passing larger vehicles and display the speed of both targets simultaneously.

29

Faster Target Locking Is Available Through Remote

The entirely redesigned IR cordless remote moves all controls into the palm of the operator's hand. Now, in addition to Stronger target locking, Faster target locking has been added. Other new remote control features include "snap" feedback keys, a smaller contoured body, and reorganized controls as well as bright amber back-lighted keys for night use and omni-directional infrared operation that eliminates the need to carefully point the remote.

Same / Opposite
[SAME/OPP] Switches between same lane and conventional opposite moving modes.

Antenna Select
[ANT] Selects front or rear antenna.

Radar Mode
[MOV STA] Toggles between four operational modes: moving, stationary closing, stationary away, or stationary bi-directional.

True Range Adjustment
[SEn 100] Selects one of four sensitivity settings, to work from approximately 1/10th mile to over 1½ miles!

Enhanced Self-Test
[SELF TEST] Performs a full diagnostic check on the display / counting unit and the selected antenna. Following a light segment test, the DSR tests the internal processor and memory, followed by a check and display of three clock frequencies, and ending with a display of input battery voltage and internal operating temperature. A comprehensive test is also performed on the selected antenna to ensure the integrity of the antenna cable and electronics.

Keyboard Backlight
[LIGHT] Activates the keyboard lights for about 6 seconds. Additional depressions cycle the display intensity through six levels of brightness.

2 Lock / Release Modes
[STRONG LOCK/REL] Transfers target window contents into lock window. Also clears lock window. This key also starts and stops the stopwatch mode.
[FAST LOCK/REL] Now, the operator has a choice with the addition of faster target locking.

Xmit / Hold
[XMIT/HLD] Toggles the radar transmitter on or off.

Stopwatch Mode
[STOPWATCH MODE] Allows the operator to time vehicles over known distances to measure speed. The stopwatch mode emits no radar signal and will not alert any radar detectors.

Lowest Patrol Speed Cutoff
[PS 5/20] Selects either a 5 or 20 mph lowest patrol speed operation.

Patrol Speed Blanking
[PS BLANK] An incorrect patrol speed can be blanked and reacquired; or after a target lock, the patrol speed can be blanked and restored.

Squelch
[SQL] In the normal position, audio will only be heard when a target is present.

Audio Volume
[SPEAKER ICON] Individually adjusts the loudness of the Doppler audio, the voice, and alert tones.

WATERPROOF Ka-Band Antenna
The Stalker DSR is available with one or two O-ring sealed, ultra-high frequency, Ka-band antennas. These compact, completely waterproof antennas include locking connectors and can be exterior mounted with no reliability concerns.

Narrow Beam-Width
The narrow antenna beam-width of 12 degrees improves target discrimination.

Patented, RFI Immune Digital Antennas
The Stalker DSR achieves the industry's longest range by digitizing the Doppler audio signal at the antenna and using a high-speed bi-directional communication link to transmit data between the antenna and the counting unit. Traditional two-piece radar units send a low level Doppler audio signal from the antenna to the counting unit for processing and speed display. This method is susceptible to noise induced by the auto ignition and 2-way radio transmissions, which results in reduced range and increased potential for false targets.

Patented Digital Antennas...

...a STALKER exclusive.

STALKER

Four Generations of Leadership

Stalker ATR

1

- Digital Signal Processing (DSP)
- Ka-Band Microwave Frequencies
- Cordless, Battery Powered Operation
- The First Long-Range Radar
- Software Controlled and Upgradeable

1991

Stalker Dual

1995

2

- Digital Antenna
- Infrared Cordless Remote Control
- Strongest & Faster Speed Tracking
- Dual Balanced Micro-Strip Antenna
- Detachable Display Unit
- True Waterproof Antennas

Stalker DSR

3

- Direction Sensing Technology
- Automatic Same-Lane Tracking
- Selectable Stationary Directional Tracking
- VSS Mode Operation
- Quad Mixer - Twin Channel Processing
- Voice Verification of Target Information

DS Direction Sensing

1998

Stalker DSR 2X

2X Multi-Direction Safety Radar

2003

4

- Rear Traffic Alert Warns Officer
- Two Complete Radars in One Package
- Monitors 2 to 4 Target Zones
- Direction Arrows for All Speed Windows
- Locks Any Displayed Target

The Industry Innovators

Applied Concepts, Inc., formed in 1977, introduced the first Stalker radar to the law enforcement industry in 1990. Because of the technology introduced by the Stalker product line, the entire police radar industry has been transformed from a complacent "me too" industry to a very dynamic "state-of-the-art" industry with all competitors trying to play "catch up" with the Stalker products. Stalker Radar has become the dominant Doppler radar system and continues to lead the industry in technology breakthroughs and product innovations. Stalker team members were involved in almost every significant radar-based product development since 1970 including:

- The first solid state police radar
- The first moving traffic radar
- The first K-Band radar
- The first K-Band handheld radar
- The first microprocessor radar
- The first Ka-Band radar
- The first cordless radar
- The first DSR radar
- The first "long range" radar
- The first digital antenna radar
- The first radar simultaneously tracking strong and faster
- The first direction sensing moving radar
- The first radar with Automatic VSS Calibration
- The first radar with Automatic VSS STA/MOV switching
- The first radar that simultaneously monitors 2 moving zones or 4 stationary zones
- The first radar with Rear Traffic Alert

Stalker will continue to innovate and to demonstrate the ability to lead all competitors.

Direction Sensing Technology

Doppler Radar works by transmitting a signal at a known frequency, and when that signal is reflected off moving objects, its frequency is shifted. Doppler radar systems measure the "absolute" change in frequency, often referred to as the "Doppler frequency." The Doppler frequency is the same for objects approaching or going away. The Stalker DSR takes an ingenious (and patented) approach to measuring the Doppler frequency. Each antenna has two sets of microwave circuits and two sets of amplification / digitizing circuits. The two microwave circuits are designed to provide two simultaneous Doppler signals with a 90-degree phase difference depending on direction. The digitized Doppler information is sent to the Digital Signal Processor, which performs a Complex Fast Fourier Transform computation to obtain relative direction for each target.

Direction Sensing Technology
Invented, Designed, and Patented by Stalker

31

Appendix IV Forms Used to Record Radar Performance during Field Testing

MF .)- 4.5

Date: 9/18/07	Time Begin: 3:00 PM	Time Ending:	Location: I 95	Temperature: 67°	Weather: CLEAR	Humidity: 52%

Vehicle Type	X-band Reading	Ka-Band Reading	Distance - Moving
SUV	69	69	100'
TRK	70	70	"
TRK	63	63	"
TT	70	70	"
TT	63	63	"
CAR	90	89	"
CAR	68	68	"
TT	65	65	"
TT	60	60	"
TRK	60	60	"
PKUP	68	68	"
PKUP	78	78	"
TRK	58	58	"
TT	74	73	"
SUV	65	65	"
CAR	67	67	"
CAR	69	69	"
TT	59	59	"
TRK	66	66	"
TRK	68	68	"

General Comments:	MPH - K 55	MPH BEE III	Page 1 of 3

32

Appendix V Pictures of Vehicle Used for Testing

Figure A.1 Testing during snow conditions

Figure A.2 Test radar units mounted on dashboard

Appendix VI Minutes of Meeting with Representative of Attorney General's Office

Ka-band Radar Research Meeting Minutes, November 7, 2007

Present: Sgt. Greg Williams, NJ State Police; Dr. Allen Katz, TCNJ/LTI and John J. Dell' Aquilo, Attorney General's office

This meeting was held at the School of Engineering Dean's Conference Room at The College of New Jersey to review the study's results and insure they are in a format that is most effective for use in the New Jersey Court system.

1. Dr. Katz distributed copies of the sections of the 3rd Quarter Progress Report dealing with the radar test results and their statistical analysis. He discussed these results and how the measurements were taken. He reported that all measurements were made in comparison to a MPH K55 X-band radar unit, that more than 1,000 measurements had been taken in different forms of weather including rain and snow, that all measurements were made under actual traffic conditions with a variety of vehicles and with the two leading Ka-band radar units.

2. Mr. Dell' Aquilo noted that the K55 X-band radar is the legal standard in New Jersey, and that comparing all measurements to this radar was appropriate and should be an effective way of substantiating the study's results in court. He felt having the study conducted by a group that is independent of the State and the use of real traffic conditions added to the study's credibility.

3. Mr. Dell' Aquilo suggested that the publication of the results of the study was another way of increasing the report's credibility and validating the results. Dr. Katz said he would investigate appropriate venues for publishing the study's results and that publication should be achievable.

4. Mr. Dell' Aquilo distributed a copy of a 1998 New Jersey Superior Court Proceedings dealing with the validity of Laser Speed Detection that could be used as a model for our study.

5. Dr. Katz discussed technical issues (as antenna pattern and beamwidth) that could affect a radar's performance. He said the technical specifications of the radar units used in the tests would be included in the final report.

6. Mr. Dell' Aquilo suggested that the specifications should be referenced to the standards of the National Highway Traffic Safety Administration (NHTSA). He also recommended Sergeant Fist Class Steve Ritter of the New Jersey State Police as a contact for highway traffic safety information.

7. Dr. Katz and Sgt. Williams thanked Mr. Dell' Aquilo for his time and very valuable assistance.

8. The next meeting is planned for November 30th to discuss the final report.

Appendix VII Laser Speed Detection Literature Search

1. Sekine, M., Senoo, T.,   Morita, I., Endo, H., **Design method for an automotive laser radar system and future prospects for laser radar,** Proceeding of the Intelligent Vehicles '92 Symposium, pp. 120 – 125, June 29, 1992

Summary: Presents a technical explanation of the specific procedure used in designing an automotive laser speed detection system. Laser radar represents an effective collision avoidance technology that can contribute to improved vehicle and traffic safety. An analysis is given of the problems involved in the practical application of laser radar and ways of overcoming them. The future prospects for automotive laser radar are also discussed.

2. Verly, J.G., Delanoy, R.L., **Model-based automatic target recognition (ATR) system for forwardlooking groundbased and airborne imaging laser radars (LADAR),** Proceedings of the IEEE, Vol. 84 , pp. 126 – 163, Feb. 1996.

Summary: We describe an experimental, model-based automatic target recognition (ATR) system, called XTRS, for recognizing tactical vehicles in real or synthetic **laser**-**radar** (LADAR) range and intensity images corresponding to a forwardlooking, CO_2 **laser radar** (LADAR) that is carried either on a ground vehicle or on an airborne platform. Various aspects of the system's operation are illustrated through a variety of examples. Generic techniques are highlighted whenever possible. A first such technique is the use of feature-indicating interest images to focus attention on specific areas of the input imagery. A second is the use of an application-independent matching engine for matching features extracted from the imagery against an application-dependent appearance model hierarchy that represents the objects to be recognized. A third generic technique is the system's architectures and its control mechanism. Following the description of XTRS, we discuss XTRS's recognition performance on real data collected with the groundbased version of the ladar sensor. We then provide a detailed account of XTRS's performance on synthetic datasets created to rest the limits of system performance. Finally, we briefly discuss the use of XTRS in conjunction with the airborne version of the sensor. Overall, more than 1500 range and intensity image pairs were used throughout XTRS's development

3. Vaughan, J.M., Steinvall, K.O., Werner, C., Flamant, P.H., **Coherent laser radar in Europe** Proceedings of the IEEE, Vol. 84 , pp. 205 – 226, Feb. 1996.

Summary: European work in coherent **laser radar** with 10 µm and shorter wavelength **lasers** is reviewed. Fundamental aspects include heterodyne studies of signal statistics and fluctuations, and detailed experimental and theoretical work on signal amplification and autodyne arrangements with light reinjected into the **laser** cavity. Progress with **lasers**, detectors, and modulators has led to the development of several compact robust field systems both continuous-wave and pulsed. Various ground-based programs are described including local wind field measurement and wake vortex investigation at airfields, and study of range, image, and Doppler shift of hard targets. Airborne systems have investigated avionics problems of true airspeed, pressure error, and wind shear warning. Other airborne studies include ground imaging, obstacle warning, terrain following, and a compendium of atmospheric backscattering over the North and South Atlantic. In recent years, the European Space Energy has supported studies and technology development for a space-borne wind lidar in the Atmospheric **Laser** Doppler Instrument (ALADIN) program.

4. Gronwall, C., Carlsson, T., Gustafsson, F., **Performance analysis of measurement error regression in direct-detection laser radar imaging,** Proceedings Acoustics, Speech, and Signal Processing, Vol 6, pp. 545-548, April 2003.

Summary: In this paper a tool for synthetic generation of scanning laser radar data is described and its performance is evaluated. By analyzing data from the system, we recognize objects on the ground. In the measurement system it is possible to add several design parameters, which make it possible to test an estimation scheme under different types of system design. The measurement system model includes **laser** characteristics, object geometry, reflection, speckles, atmospheric attenuation, turbulence and a direct detection receiver. A parametric method that estimates an object's size and orientation is described. There are measurement errors present and thus, the parameter estimation is based on a measurement error model. The parameter estimation accuracy is limited by the Cramer-Rao lower bound. Validations of both the measurement error model and the measurement system are shown. Data from both models generate parameter estimates that are close to the Cramer-Rao lower bound.

5. An-Ping Wang, Jie-Cheng Chen, Pao-Lo Hsu**,** Intelligent CAN-based automotive collision avoidance warning system**,** Networking, Sensing and Control, 2004 IEEE International Conference Digest, Vol. 1, pp. 146-151, March 21-23, 2004.

Summary: To construct a vehicle collision avoidance system, a laser radar and three ultrasonic sensors are integrated with the CAN bus to build the in-car network architecture to prevent the car on all directions. There are two sub-systems developed for this collision avoidance system: (a) the front-end sub-system and (b) the side and rear-end sub-system. The front-end collision warning sub-system is constructed for high-speed driving conditions by measuring the distance in the front with a laser radar. Moreover, the relative speed between two cars can be properly estimated by applying the current Kalman filter. Then, a D/V curve is further obtained to generate collision warning with a desirable precaution time to prevent the front-end collision actively. For the collision avoidance on the side and the rear-end, the approaching speed from other cars in general is slow and available ultrasonic sensors with limited range and resolution are adopted. An intelligent approach is proposed to process the rough distance readout to render warning signals with suitable timing for the approaching car drivers to prevent the collision passively. A high-level network protocol CANopen is applied to integrate all ultrasonic sensors as the in-car network communication.

6. Buhren, Markus, Yang, Bin, **A Global Motion Model for Target Tracking in Automotive Applications,** Acoustics, Speech and Signal Processing, Vol. 2, pp. 113-115, **April 15-20,** 2007.

Summary: In common automotive radar tracking systems, simple linear models are used to track targets separately in longitudinal and angular direction relative to the own vehicle (or sensor) position. Under the special condition that the observed targets are straight ahead and moving nearly in the same direction as the observing vehicle, like in adaptive cruise control (ACC) systems, those models work well. In more general scenarios, where movements of other vehicles have to be tracked in all possible directions and all around the vehicle (e.g. in inner-city or intersection situations), the modeling is insufficient. In this paper we review the drawbacks of the commonly used models and present a more general motion model for automotive tracking systems. All necessary expressions for an implementation using an extended or unscented Kalman filter are given. Even if designed for radar systems, the state model is not limited to a special type of sensor. It can be used for ultrasonic or laser scanner systems as well as for vision-based systems with a different measurement model.

7. Chiricescu, S., Chai, S., Moat, K., Lucas, B., May, P., Norm, J., Essick, R., Schuette, M., **RSVP II: a next generation automotive vector processor**, Intelligent Vehicles Symposium, pp. 563-568, June 6-8, 2005.

Summary: A large number of sensors (i.e., video, radar, laser, ultrasound, etc.) that continuously monitor the environment are finding their way in the average automobile. The algorithms processing the data captured by these sensors are streaming in nature and require a high rate of computation. Due to the characteristics of the automotive environment, this computation has to be delivered under very low energy and cost budgets. The reconfigurable streaming vector processing (RSVP/spl trade/) architecture is a vector coprocessor architecture which accelerates streaming data processing. This paper presents the RSVP architecture and its second implementation, RSVP II. Our results show significant speedups on data streaming functions running compiled code. On a lane tracking application, RSVP II shows impressive performance results. From a performance/$ and performance/mW perspective, RSVP architecture compares favorably with leading DSP architectures. The time to market is substantially reduced due to ease of programmability, elimination of hand-tuned assembly code, and support for software re-use through binary compatibility across multiple implementations.

8. Neri, C., Baccarelli, G., Bertazzoni, S., Pollastrone, F., Salmeri, M., **Parallel hardware implementation of radar electronics equipment for a laser inspection system,** Nuclear Science Symposium Conference Record, Vol. 3. Vol. 3, pp. 1352-1356, Oct. 16-22, 2004.

Summary: An amplitude modulated laser radar has been developed by ENEA (Italian Agency for new technologies, energy and environment) for periodic in-vessel inspection in large fusion machines (ITER). The system is able to obtain a complete 3D mapping of the in-vessel surface. First, a digital signal processing system was developed to modulate the laser beam and to detect both the amplitude of the back scattered light and the phase difference between it and the modulation signal. This system is based on commercial digital receiver and parallel DSP (digital signal processing) boards on a VME bus. It reaches a speed of 100 K measures/s showing good accuracy and stability. Starting from this, further development has been done to increase the speed up to 2.328 M measures/s. To reach the sub-microsecond speed it was necessary to implement the mathematical algorithm in a highly parallel hardware architecture using FPGAs (field programmable gate array). Looking at the good results of previously developed system it was decided to maintain the same acquisition front-end. The last release of A/D converters was used to increase the operating frequency up to 200 MHz, but the previously used software algorithm was completely redesigned and optimized to be used in the FPGA hardware architecture.

9. Hancock, J., Langer, D., Hebert, M., Sullivan, R., Ingimarson, D., Hoffman, E., Mettenleiter, M., Froehlich, C. **Active laser radar for high-performance measurements,** Proceedings of Robotics and Automation, 1998. Vol. 2, pp. 1465 – 1470, May 16-20, 1998.

Summary: Laser scanners, or laser radars (ladar), have been used for a number of years for mobile robot navigation and inspection tasks. Although previous scanners were sufficient for low speed applications, they often did not have the range or angular resolution necessary for mapping at the long distances. Many also did not provide an ample field of view with high accuracy and high precision. In this paper we will present the development of state-of-the-art, high speed, high accuracy, 3D laser radar technology. This work has been a joint effort between CMU and K2T and Z+F. The scanner mechanism provides an unobstructed 360° horizontal field of view, and a 70° vertical field of

view. Resolution of the scanner is variable with a maximum resolution of approximately 0.06 degrees per pixel in both azimuth and elevation. The laser is amplitude-modulated, continuous-wave with an ambiguity interval of 52 m, a range resolution of 1.6 mm, and a maximum pixel rate of 625 kHz. This paper will focus on the design and performance of the laser radar and will discuss several potential applications for the technology. It reports on performance data of the system including noise, drift over time, precision, and accuracy with measurements. Influences of ambient light, surface material of the target and ambient temperature for range accuracy are discussed. Example data of applications will be shown and improvements will also be discussed.

10. Meng Lu, Wevers, K., van der Heijden, R., Heijer, T., **ADAS applications for improving traffic safety,** Systems, Man and Cybernetics, Vol. 4, pp. 3995-4002**,** Oct. 10-13, 2004.

Summary: Governments in several European countries, and the EU have set challenging targets for the improvement of road traffic safety by the year 2010. In the Netherlands a program for infrastructure measures was launched, to meet the Dutch targets. The ongoing developments in the field of ITS applications seem however to offer viable alternatives for large-scale infrastructure reconstruction. This paper explores the feasibility of five ADAS applications (navigation**,** speed assistance, collision avoidance, intersection support and lane keeping) to complement or partly substitute infrastructure measures to reach the stated goals. State-of-the-art and the potential of enabling technologies like positioning, radar, laser, video imaging and communication are analysed from a technical perspective. Technical issues relating to large-scale dedicated ADAS implementation for traffic safety, as well as related policy issues are discussed.

11. Fisher, P.D., Pyhtila, J.W., **Timing quantization error in lidar speed-measurement devices,** IEEE Transactions on Vehicular Technology, Vol. 49, pp. 276-280, Jan. 2000.

Summary: Minimizing the timing quantization error of lidar speed-measurement devices is an important step in reducing the magnitude of the speed-measurement errors associated with these devices. This paper presents a statistical model for the timing quantization error and demonstrates how this model can be used to select the values of key timing parameters. The values of these parameters must be carefully selected so that manufactured equipment meets current model lidar speed-measurement device performance standards established by the National Highway Traffic Safety Administration (NHTSA).

12. Kawashima, S., Watanabe, K., Kobayashi, K., Traffic condition monitoring by laser radar for advanced safety driving, Proceeding of the Intelligent Vehicles '95 Symposium, pp. 200-303**,** Sept. 25-26, 1995.

Summary: This paper describes a new method for the accurate estimation of traffic conditions around a vehicle on the road through the use laser speed measurement signals. A conventional laser speed measurement system monitors only one vehicle that is normally located just in front of the vehicle taking the measurement. This research aims at developing a new traffic condition monitoring system that can monitor 8 to 10 vehicles located around the measurement vehicle by more fully utilizing the reflected laser signals.