Radar for Traffic Monitoring

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Final Research Report

Radar for Traffic Monitoring

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Technology Service Corporation (TSC) investigated the technical feasibility of building a traffic monitoring sensor based on a police speed radar. This sensor would provide estimated vehicle counts and speeds along an extended stretch of remote roadway. TSC evaluated the visibility from two WSDOT towers that were suggested as demonstration test sites. A radar system configuration was designed for future implementation and required components were identified.</td></tr>
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1.0 Executive Summary

The problem that this report addresses is the monitoring of traffic in remote, extended areas where it is too expensive to install and maintain embedded roadway sensors. TSC proposes a modestly priced radar that would be mounted on towers at selected locations to measure the count and speed of moving vehicles. This data could be used to predict travel time, provide driver alerts and analyze congestion. In this research effort, TSC analyzed the road visibility from candidate radar locations and assessed the feasibility of building affordable radar. This radar is based on a commercially produced police speed radar that offers more capability than side-looking radars which have limited range and lack inherent speed measurement. TSC proposes a demonstration program to build a prototype system. The hardware cost is a modest $29K but significant engineering labor is required to fabricate and test the radar, collect sample data, develop new radar signal processing software and conduct a demonstration experiment. Actual deployment costs can be better estimated once a prototype radar is built and demonstrated. At a minimum, the deployment costs would include the construction of towers (50-100' may be adequate) at selected road locations (probably 3-5 km apart). Power must also be provided for radar operation and a radio or other data link to a central location is needed.

2.0 Introduction and Purpose

Washington State DOT (WSDOT) currently performs traffic monitoring to better understand causes of congestion, to plan road improvements and to manage traffic through ramp metering, travel-time estimation and alternative route recommendations. An additional use of traffic monitoring is federal reporting of road usage for gas tax reimbursement to the state. The purpose of this study was to investigate the feasibility of building a low-cost hill-top or tower-mounted radar to perform remote traffic monitoring and to estimate the cost to conduct a demonstration test at a candidate location.

Radar offers an alternative to magnetic-loop sensors embedded in the roadway. These are currently employed on highways in built-up areas where the constant, large volume of traffic warrants their use. Such embedded sensors are both disruptive and expensive to install and maintain. Thus they are considered impractical for remote, rural areas where the sensors are vulnerable to road surface damage and raw data must be communicated back great distances to a central facility.

Radar traffic monitoring appears to be ideal for such remote road locations. Multiple units would be employed to cover long stretches of roads at sufficient intervals to measure the overall traffic speed and volume to support congestion analysis and alternative route recommendations by radio broadcoast or electronic sign display. The radar measurements would be locally processed and traffic metrics sent periodically to a central DOT facility via a telephone modem or radio link with low communication bandwidth.

A recent, published study compared Doppler radar, video, acoustic and infrared sensors for traffic monitoring and concluded that radar afforded a medium cost solution with excellent detection and speed measurement but poor car versus truck classification capability [1]. It is helpful to understand how radar works to see its potential benefits and limitations for traffic monitoring. Doppler radars, such as the ubiquitous police radar, measures the speed of any vehicle that falls within its radar beam by the shift in the frequency of the reflected signal. The width

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1. Duckworth et al, "Comparative Study of Non-Intrusive Traffic Monitoring Sensors", SPIE Vol. 2344, Intelligent Vehicle Highway Systems, 1994, pp. 16-29.

of the radar beam depends on the antenna size. For police radar, the antenna need not be large since the target vehicle is relatively close in range and the beam does not spread out much. For longer range operation, the antenna can be made large to decrease the beamwidth and focus on single vehicles. A larger antenna also increases the received signal strength allowing vehicles to be detected at greater ranges. This is advantageous for traffic monitoring where it is desirable to cover a single highway of interest when there are nearby side roads with vehicles that can contaminate the measurements. Detecting vehicles over extended distances also allows fewer radar units to be employed.

The low-cost radar transceiver in a police radar unit forms the basis of TSC's system design. A larger antenna is added to both narrow the beamwidth and extend the range. However, in a police radar, only a single vehicle's speed can be measured because it employs continuous waveform (CW) transmission. TSC's approach is to use frequency sweeping so that multiple vehicles can be detected and their speed measured simultaneously. This requires a slight enhancement of the basic transceiver that the manufacturer currently provides at nominal cost.

It should be noted that radar detection is imperfect and that false alarm events caused by random receiver noise and clutter interference, such as wind-blown trees, can occur. Furthermore, individual vehicles must be separated in distance along the roadway by at least the radar range resolution to be detected individually. Vehicles that are traveling close together in one lane or moving in parallel in two lanes (or on parallel roadways) are detected as a single object if they have approximately the same speed and direction. (The proposed radar can always distinguish vehicles moving in opposite directions toward or away from the radar regardless of their spacing based on Doppler frequency shift.) Thus only an approximate vehicle count can be obtained with radar. This count can potentially be corrected using a scaling factor for dense traffic. In addition, speed accuracy will decrease in dense vehicle environments since only a composite Doppler frequency shift is measured at each range cell. This is not an issue if all the traffic is moving at roughly the same speed.

It must also be noted that Doppler radar cannot detect stationary objects. In fact, there is a minimum detectable velocity (MDV), on the order of 5-15 mph depending on radar sensitivity, below which vehicles are not detected. Computer processing can be used to determine when the traffic slows below this MDV limit because of a traffic jam and vehicles are no longer detected even though they are present.

Radar units must be placed on towers or on hillsides to gain visibility of distant road sections because of the horizon effect and line-of-sight (LOS) blockages along the highway from objects such as trees, signs and buildings. Radar microwaves bend somewhat in the atmosphere which extends this horizon slightly compared to the visual horizon. Nonetheless, towers of a hundred or more feet may be required to monitor the traffic on roadways through hilly areas. It is not necessary to cover every foot of contiguous roadway and some gaps in valleys or behind hills will be acceptable for most traffic monitoring applications. Careful siting must be performed to optimize road coverage and minimize radar equipment and tower expense in hilly areas. TSC performs similar siting analysis for the FAA and NAVCAN for airport surveillance radars.

TSC initially investigated hill-top sites to conveniently place radar units, but was discouraged by WSDOT engineers because of the significant tree blockage in most areas and the tree clearing required for site emplacement. As an alternative, WSDOT recommended two tower sites that are suitable for experimental radar testing of traffic monitoring on the I-5/I-205 corridor in southern WA where traffic feeds into Portland, OR. These sites are: 1) a 300 ft tower at the

Vancouver DOT office along I-205 and SR-500 and, 2) a 200 ft tower along I-5 at an older DOT facility. TSC performed a detailed visibility analysis of the terrain and roads near these two towers to guide the radar system design. A preliminary radar system was then designed and the cost to build a prototype radar system and collect measurements was estimated.

3.0 Summary of Findings

TSC performed a number of technical tasks during this brief study. A LIDAR database was acquired through WSDOT to analyze the road visibility for a radar mounted on each of the towers. This LIDAR database was in a standard raster format that was initially divided into vegetation and man-made land cover. These had to be merged and imported into TSC's Radar Support System to determine the true radar line of sight visibility. Road vectors were also overlaid on the visibility map to indicate key areas of radar coverage so that multiple antennas could be specified.

TSC established the radar performance requirements for traffic monitoring and reviewed the functionality of a police radar transceiver. TSC also assessed its performance limitations with respect to range and Doppler speed measurement. A preliminary radar system design was then developed for the experimental demonstration and all crucial components were specified. The cost to build a radar unit and conduct an experimental demonstration was also estimated.

TSC believes that a low-cost police radar transceiver can be readily modified to provide a very effective traffic monitoring radar system. A prototype radar system can best be demonstrated by monitoring traffic along SR-500 or I-5 at the 300 ft. tower site. Multiple antennas would be mounted on this tower along with other radar hardware weighting less than 100 lbs. A radio link to a van containing a data recorder, processor and display equipment will permit either a live demonstration to WSDOT engineers or a playback demonstration at WSDOT offices. TSC estimates a rough cost of $443K to purchase the hardware, develop the radar and processing software, and conduct an experimental test demonstration. The effort could be completed in a 10 month schedule by 2 TSC engineers working full-time. We would be pleased to provide a detailed proposal listing labor, material and travel costs if requested.

Several minor issues should be resolved before proceeding. First, any radio frequency interference (RFI) constraints for the radar and data link operations at the Vancouver DOT site must be investigated. TSC proposes to uses an X-band (10.0 to10.55 GHz) radar operating frequency that is unlikely to cause interference with other communications equipment on the tower or nearby. Second, tower mounting options, wind loading restrictions and weight limitations must be better understood. The person responsible for tower maintenance indicated that the proposal antenna weight and size should not be problematic. This person was not available to review TSC's proposed design during the study period. Finally, support for installing equipment on this tower should be identified within DOT or one of its contractors.

For eventual deployment at other sites, optimal placement along roadways of interest and system costs including providing power and data communication links must be addressed. Methods to distinguish cars from trucks based on multiple radar measurements should also be investigated. The experimental data provided in the demonstration can be used to investigate candidate methods with ground truth provided by video cameras mounted along on the highway. It is assumed that WSDOT has the resources to accomplish such ground truthing.

Besides WSDOT, other state DOT and federal agencies could potentially take advantage of this proposed technology. The FAA has solicited concepts for low-cost runway monitoring systems under past BAAs. DoD force protection could also benefit from monitoring vehicle traffic approaching bases such as nearby Fort Lewis. Homeland Security for national events such as the 2010 Winter Olympics in Vancouver could additionally benefit from this technology. These additional uses offer opportunities for cost-sharing that will be investigated by TSC. In this way, WSDOT would not need to fund the entire demonstration program. One promising option is matching funds from the Air Force for any WSDOT contribution under SBIR Topic AF02-099.

4.0 Appendices

TSC performed a detailed technical study that was documented in the form of a standalone appendix for each of the key tasks. Appendix I describes the road visibility from the candidate tower sites since this is a driving factor for radar antenna selection. Appendix II describes the multiple antenna configurations that were designed to cover the visible roadways of interest. Appendix III provides a high-level description of the proposed radar system and the auxiliary components required to conduct a test. Appendix IV describes the radar transceiver which is at the heart of TSC's design and discusses critical performance issues. Appendix V lists the complete list of components, various vendors, cost and weights. Finally, Appendix VI provides a brief cost breakdown for the planned demonstration program.

Appendix I. Road Visibility from Candidate Towers

The primary factor in the suitability of a radar site for traffic monitoring is visibility to the road(s) of interest. If visibility to a road is blocked by intervening terrain, then a higher tower or alternative site must be found. On the other hand, the radar need not be designed for any greater range or angular sector than is needed to cover the visible road(s) from the site. Additional radar antenna can always be installed to cover roads in multiple directions.

To evaluate the visibility of road segments from the two proposed tower locations, TSC created a Digital Elevation Model (DEM) based on LIDAR data of Clark County provided by Washington State DOT. This LIDAR based DEM included first reflection surfaces such as trees and buildings, and thus provides a very accurate estimate of the LOS visibility to vehicles on road surfaces. TSC's Radar Support System (RSS) was used to determine the visible extents of the major highways in the Vancouver area for the two towers listed in Table I-1.

Table I-1 Tower Locations

Latitude	Longitude	Height
45° 39' 37"N	122°33' 34W	300'
45° 37' 42"N	122°39' 56W	200'

The RSS determines the minimum visible height of an object at any point based on the DEM and radar location/height. The header across the top of Figures I-1 through I-6 provides radar coordinates. The color code at the upper right indicates the height above ground level in feet that an object must be. Most vehicles are less than 10 ft. tall and so are only visible in areas colored white in these plots.

Each of the following coverage plots shows the highways of interest in colored bold lines of red (I-205) and green (SR-500). The radar angular sector required to cover most of the roadway is shown as a pair of black or cyan lines. A summary of the size of the range and angular sector required for each case is summarized in Table I-2. TSC recommends using the 300ft tower for the demonstration and monitoring SR-500 to the west as shown in Figure I-2. A good alternative is monitoring I-205 to the northwest or south. These two choices afford a modest angular sector and sufficient range extent to prove feasibility.

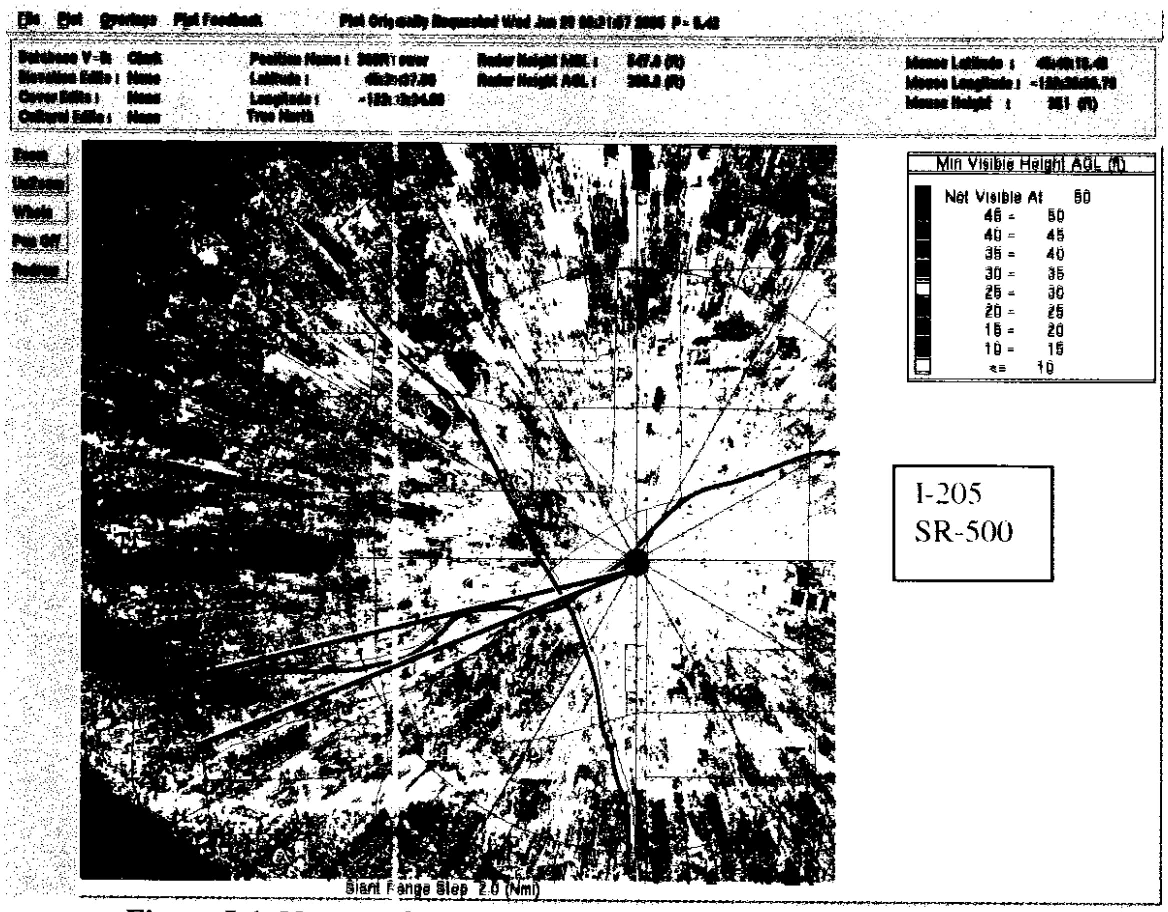

Figure I-1 Narrow Coverage from 300 ft Tower of SR-500 to West (2 Nmi Range Rings)

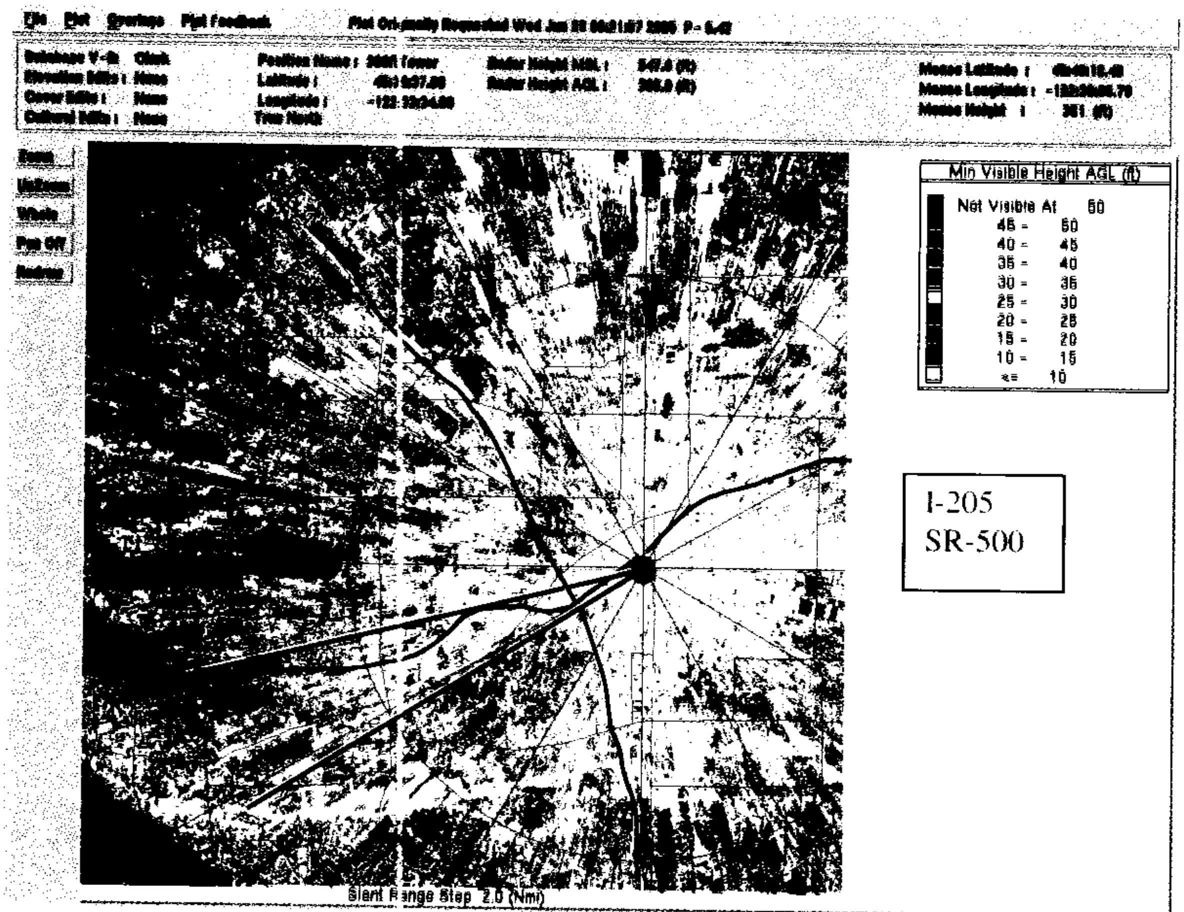

Figure I-2 Extended Coverage from 300 ft Tower of SR-500 To West (2 Nmi Range Rings)

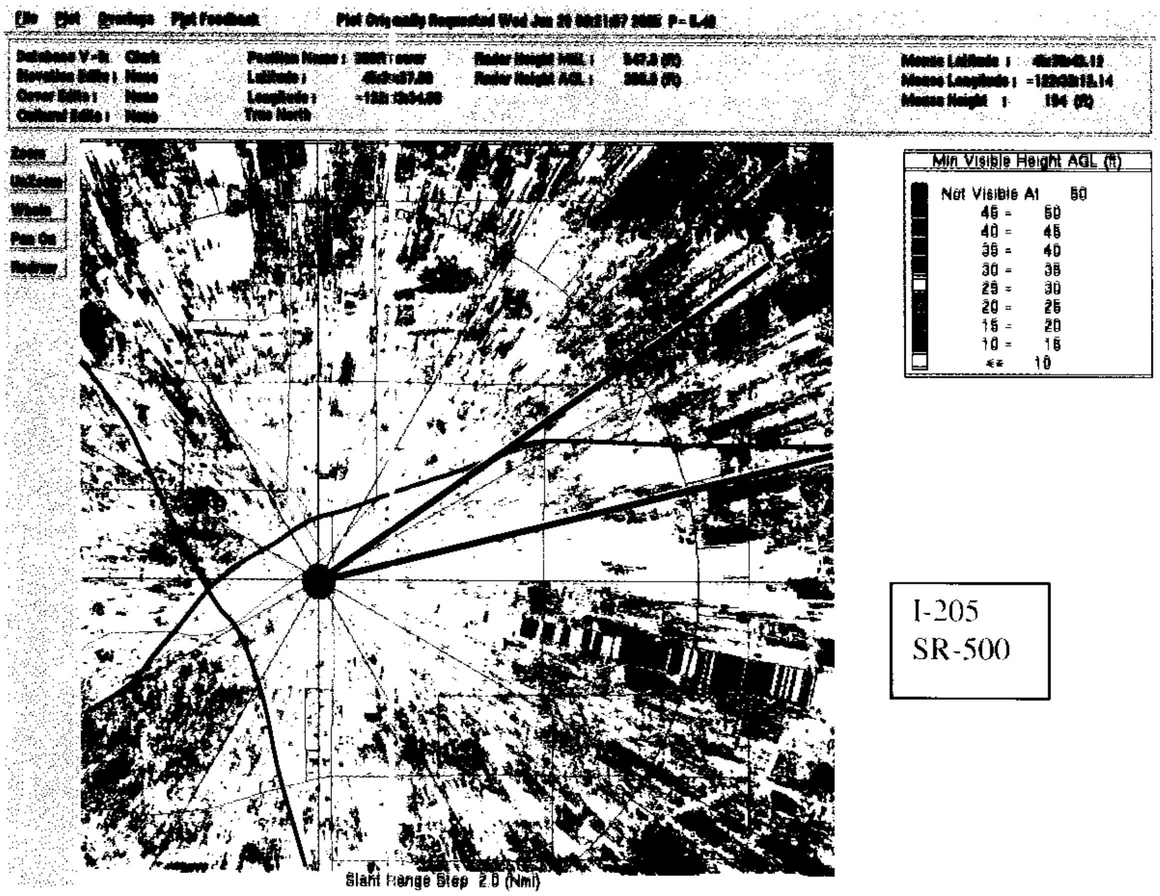

Figure I-3 Nominal Coverage from 300 ft Tower of SR-500 To East (2 Nmi Range Rings)

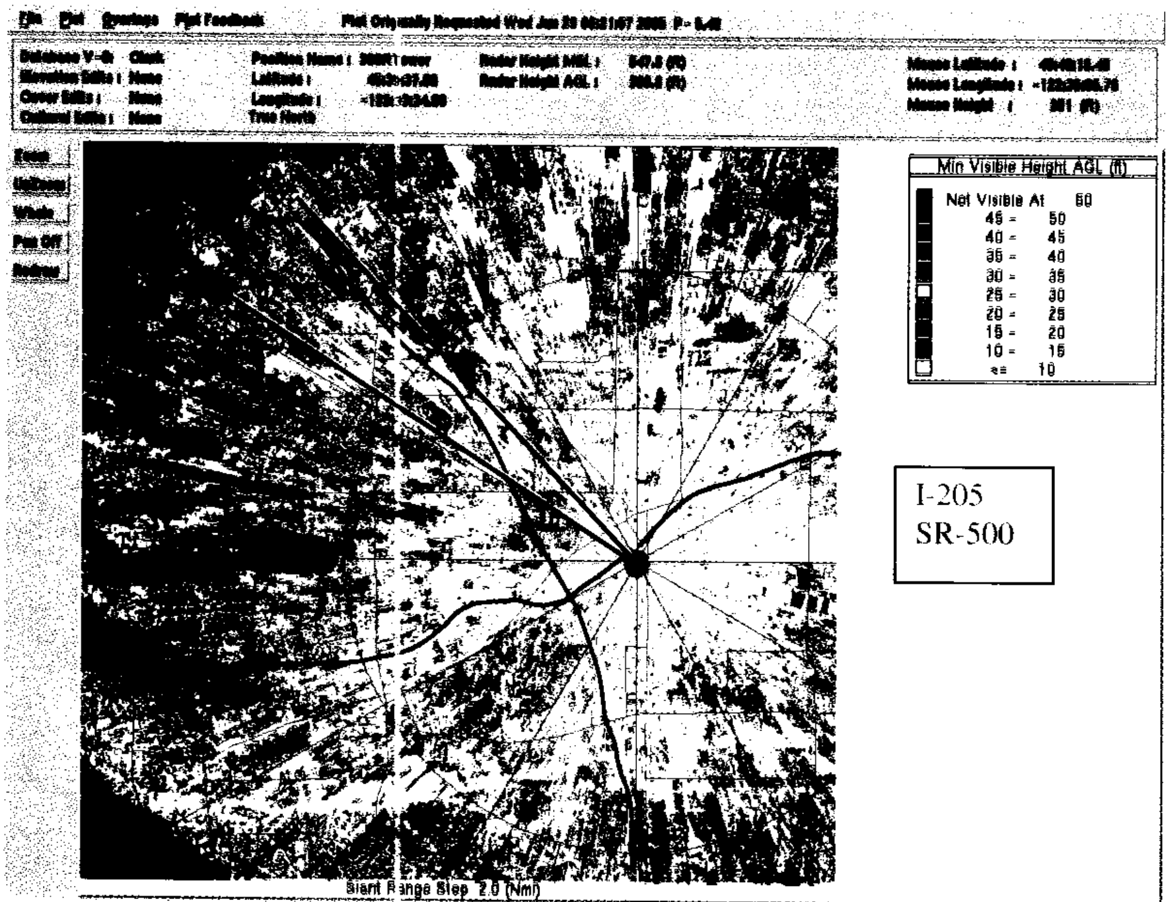

Figure I-4 Possible Coverage from 300 ft Tower of I-205 to the North West (2 Nmi Range Rings)

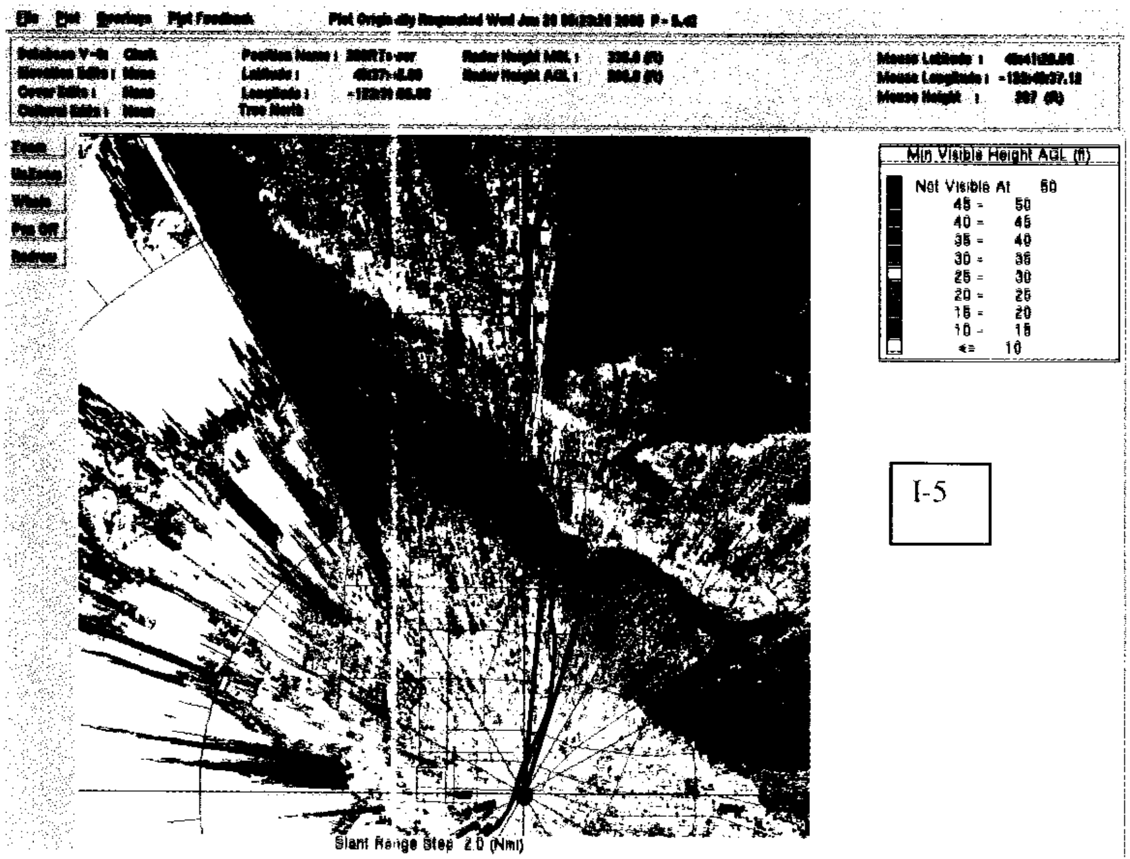

Figure I-5 Nominal Coverage from 200 ft Tower of I-5 to the North (2 Nmi Range Rings)

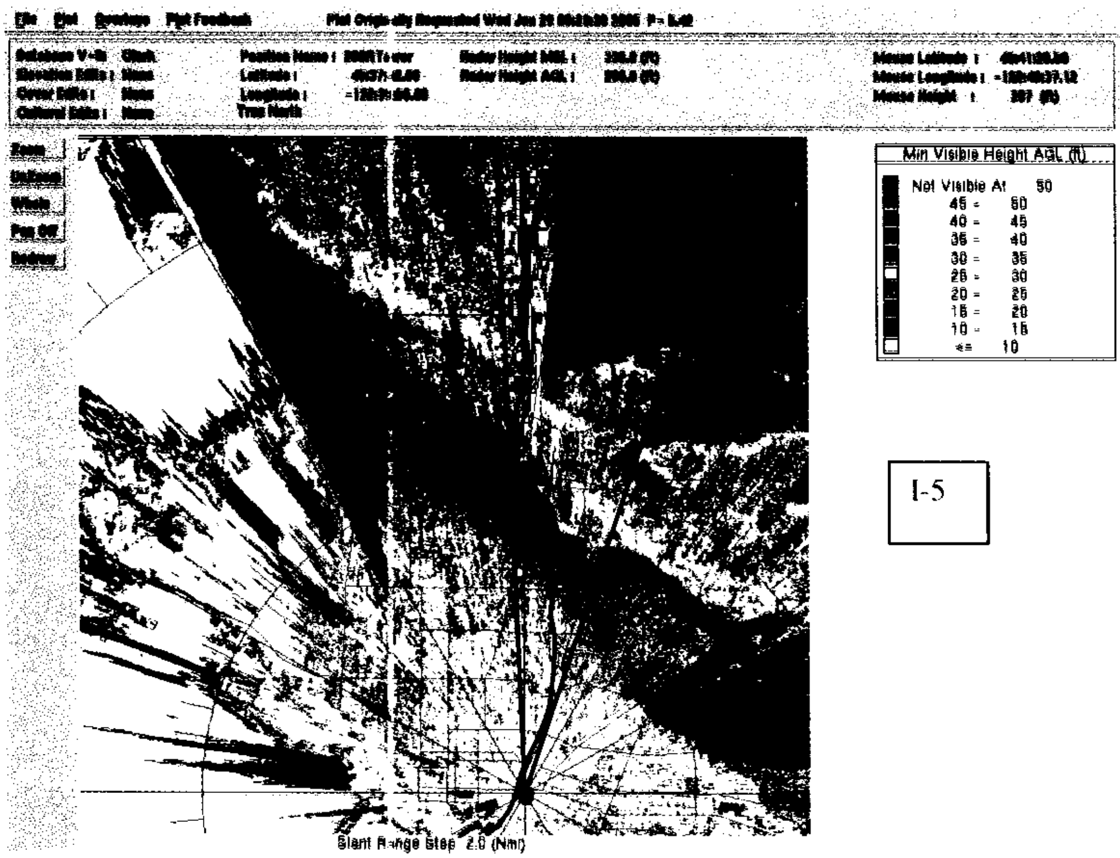

Figure I-6 Extended Coverage from 200 ft Tower of I-5 to the North (2 Nmi Range Rings)

Table I-2 Radar Extents Required for the 6 Cases

Case	Range Extent (Nmi)	Azimuth Extent (deg)
300ft Tower SR-500 West	3.4	9
300ft Tower SR-500 West Extended	3.4	18
300ft Tower SR-500 East	3	20
300ft Tower I-205 NW	3.2	15
200ft Tower I-5 North	1.6	15
200ft Tower I-5 North Extended	4	20

Appendix II. Antenna Configuration

TSC developed a radar antenna configuration for the 300' tower which is the recommended test site. The selection of antenna sizes, pointing angles and types depends on the road extent that is visible from the tower including its minimum/maximum range and angular sector. A single, large antenna is sufficient to view I-205 to the northwest or south. However, two antennas, one small and one large, are required to cover the larger range and angular extent of SR-500 which is visible. It is also possible to only use a single antenna and only cover a portion of the visible roadway for demonstration purposes. This would only slightly lower the cost but greatly reduce the amount of data that could be collected.

The low power of the Doppler transceivers necessitates that the antenna have sufficient electrical gain to provide good received signal-to-noise ratio (SNR). However, along with high gain comes narrow beam width, and this will limit the coverage provided by any one beam. So, the problem is to design a system that balances the requirements for high antenna gain with the need to cover the traffic on the intended highway and not side roads. Options that are available include multiple beams, multiple antennas, or some form of mechanical or electronic beam scanning. It is noted that the narrow beam width in azimuth, at least, will aid the vehicle speed measurement process by limiting the traffic from side roads in each range cell, which would otherwise contaminate the processing.

The lowest cost, lowest risk antenna solution is to use a parabolic dish antenna mounted near the top of the available 300 foot tower. A spreadsheet model of the beam of such an antenna was developed to graph the footprint of the beam along a radius from the base of the tower outward. This "footprint" consists of the power received from a vehicle target vs. range. An output from this model is shown in Figure II-1 below:

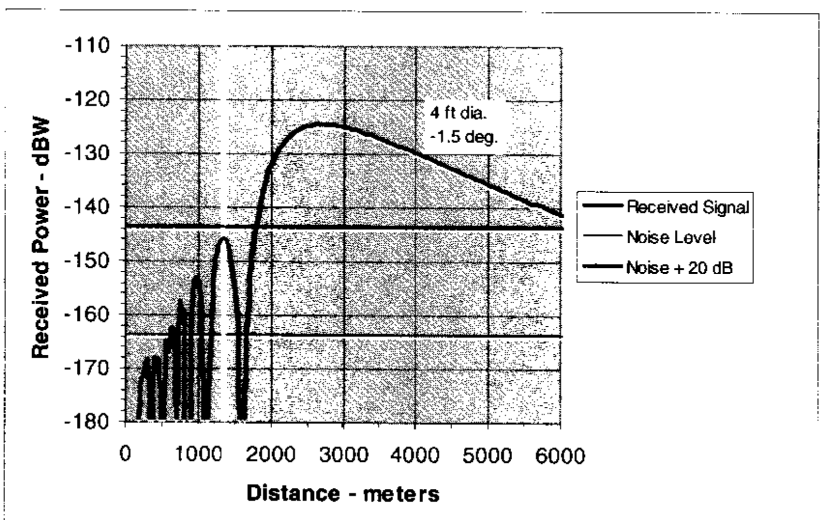

Figure II-1 Footprint of 4 ft. dish antenna on 300 ft. tower

The plot shows the power received as a function of the distance of a vehicle target (Radar cross section = 5 m^2), using a 4 foot diameter parabolic dish antenna. This antenna size is the minimum required and has a pencil beam of about 1.7° beam width. Also shown on the graph is the receiver noise level in a 10 Hz processing bandwidth, which is at about -164 dBW. The distance scale stops at 6 km because the visibility plots indicate that roads and traffic will be visible only out to about 3 to 3.5 nm from the tower, so more sensitivity would not be of use. Based on standard radar performance requirements, at least 20 dB signal-to-noise ratio is needed for adequate Doppler processing and speed measurement, so a horizontal line is shown at that level. The antenna is depressed to an angle below horizontal of 1.5°. This is chosen to both maintain the received power out to 6 km and inward as far as possible. Even so, the distance from 0 to about 1.8 km is not covered since the elevation beam width cuts off the received signal. Various ways were considered to also cover this area, but the lowest cost, lowest risk solution is to add two more radar transceivers and smaller antennas.

The plot in Figure II-2 shows the output of the model when several antennas and transceiver units are mounted on the tower at the same location:

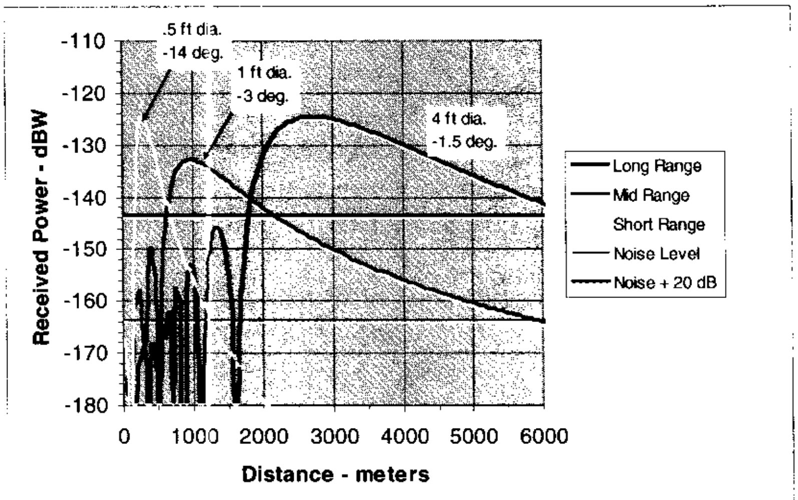

Figure II-2 Footprints of 3 antennas collocated on tower

Here, one antenna of 1 foot diameter (7° beam width) and one of ½ foot diameter (14° beam width) have been added. They are shown with their beams in the same vertical plane as the original 4 foot diameter antenna. Note that together their footprints cover the entire distance from 6 km down to about 0.2 km with better than 20 dB SNR at all ranges.

Approximate renditions of the corresponding footprints on the ground for each of the transceiver/antennas, are superimposed on the coverage plot in Figure II-3. The elliptical footprints are shown in the same corresponding colors as in the chart above. The elevation angles in each case are adhered to, but their azimuth angles have been adjusted to better cover SR-500. Also shown are the footprints for two additional 4 foot diameter antennas that are aimed to cover parts of I-205. These illustrate the coverage that would be available along I-205 using two similar 4 foot diameter antennas. The additional complexity and cost to mount these two dishes on the tower may be justified for the test demonstration.

It is important to note that the performance of the radar is very insensitive to the height of the antennas on the tower. That is, they could be located as much as 30 or 40 feet lower than the top and would still work very well. The only exception to this would be if the terrain is such that this change in height would cut off the view of some parts of the roads. TSC will repeat the visibility analysis for candidate radar heights once the available tower mounting options and heights are known.

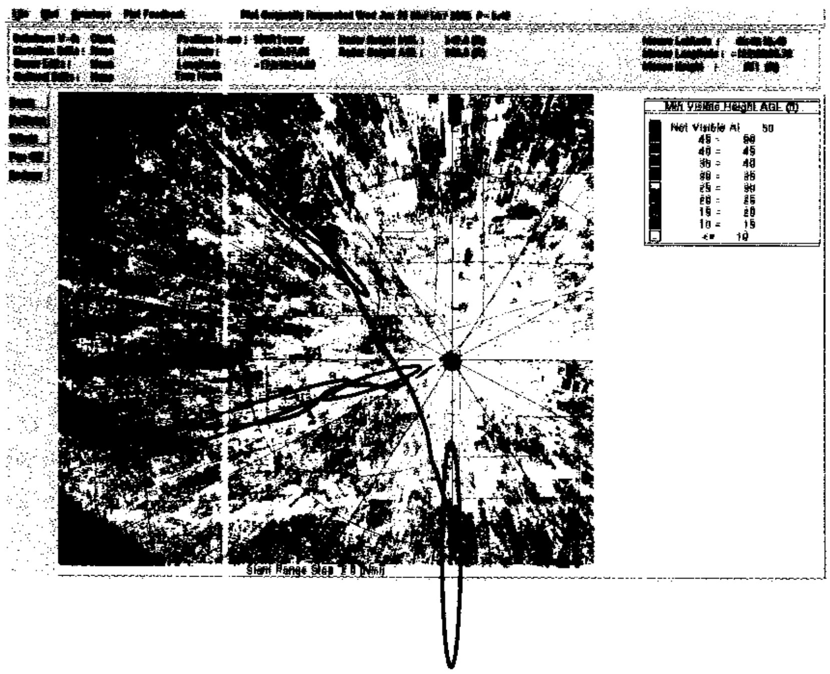

Figure II-3 Coverage plot for multiple antenna configuration
(Green = SR-500, Red = I-205)

Appendix III. Radar System Description

TSC completed the preliminary design of a radar system suitable for an experimental demonstration of traffic monitoring on SR-500. The tower portion consists of antennas, transceivers, A/D converters and serial data transmitters attached to an RF modem. For the demonstration, a test van would receive the RF data for input to a PC for local data processing and display and a single antenna could be employed to reduce system complexity and cost.

Figure III-1 below shows a block diagram of the proposed demonstration system. The components in the dashed box to the left are at the top, or near the top, of the 300 foot tower. The components in the dashed blue box on the right are in a test van at a convenient location near the base of the tower. The data and control connection is via a serial data interface link operating through a pair of RF modems. This will permit installation of the system without a long data cable descending the tower. The X-band transceivers are connected directly to the waveguide terminals of the antennas. The antennas are mounted via articulated pipe clamps to a pipe installed vertically along one corner of the tower. Each can be adjusted separately in elevation and azimuth angle. The I and Q analog outputs of the transceivers are digitized via 6 A/D converters. The data words are then loaded serially on the data bus and sent to the RF modem for transmission of the data to the ground. On the ground, the mating RF modem and serial data receiver transfer the data into memory of a PC. LabView software on the PC processor performs the range gating, Doppler processing, and vehicle speed sorting and display.

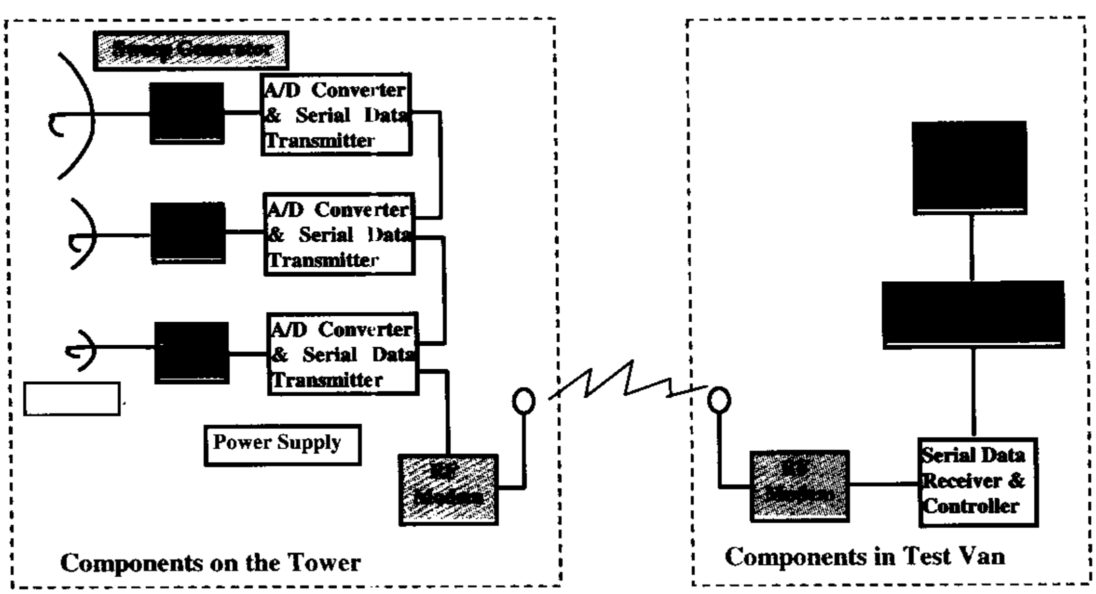

Figure III-1 Block diagram of proposed system

To accomplish range measurement, the sweep generator linearly sweeps the frequencies of the transmitters upward and downward in a triangular waveform in the first part of the pulse compression function. During a linear up sweep in frequency, the return signal from a stationary point target will be lower in frequency than the transmitted signal by a constant amount, and proportional to the distance, or time delay. During the linear down sweep in frequency, the return signal will be higher in frequency by the same amount. Any radial motion of the target will add the same Doppler frequency to both time periods. Therefore, the second part of the pulse compression function is done in the LabView processor in the PC by forming complex Fourier transforms (FFTs) of the outputs of the transceivers.

The frequency shift due to range is separated from the frequency shift due to Doppler by successively forming the sum and then the difference of the two FFTs over the two time periods. The additional processing for generating traffic statistics is well understood and can be readily performed on the PC.

Virtually all of the components and their interfaces have been employed recently, and successfully, in several different projects at TSC, in ways that are very similar in configuration and parameters to the proposed system. For example, the complete radar unit pictured below has been built as part of an array of such units for a current land mine detection project. The unit measures about 4" by 4" by 6" tall, as shown in Figure III-2 and is a complete, stand-alone radar transmitter and receiver. It needs only a connection to 120 VAC line power. It has both analog and digital outputs that can be sent to a PC based processor. The square object at the bottom of the unit is the current antenna, which would not be suitable for the traffic monitoring demo. Instead, this antenna would be replaced by either the 4 foot or 1 foot dish, or a ½ foot horn antenna, with only a minor modification to the housing needed.

The photo in Figure III-3 shows a portable PC that would be used for radar processing together with its special hard case for shipping. The PC contains a special card that receives the digital data stream from multiple radar units and stores them in memory. The LabView software can perform all of the necessary radar signal processing and present the results on the screen for testing. Changes can be made to the LabView program or additional Matlab software can be developed to extract vehicle velocities, locations, and compute various traffic statistics.

The demonstration system described in this section, with the 4 foot, 1 foot, and ½ foot antennas should have the capability to measure vehicle speeds, and direction, over a distance from about 200 meters to over 6 km from the base of the 300 foot tower. This includes all of the visible portions of SR-500. It should measure vehicle speeds from about ±5 mph to over ±100 mph, with a resolution of ½ mph. The lower limit of speeds will be dependent on the amount of clutter motion, due to wind blown trees, etc. that competes with the reflections from the vehicles. The extent of this interference will be analyzed and evaluated experimentally. Appropriate signal processing will then be implemented to reject it. In addition, the range resolution of the radar will be about 10 feet meaning that it should be able to resolve vehicles that are separated by about 1 vehicle length. An expansion of the system to additionally cover I-205 would not be difficult.

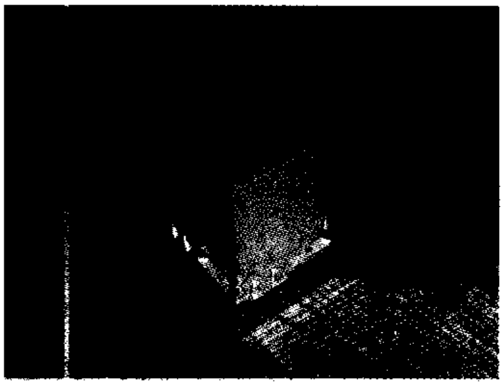

Figure III-2 Land Mine Detection Radar

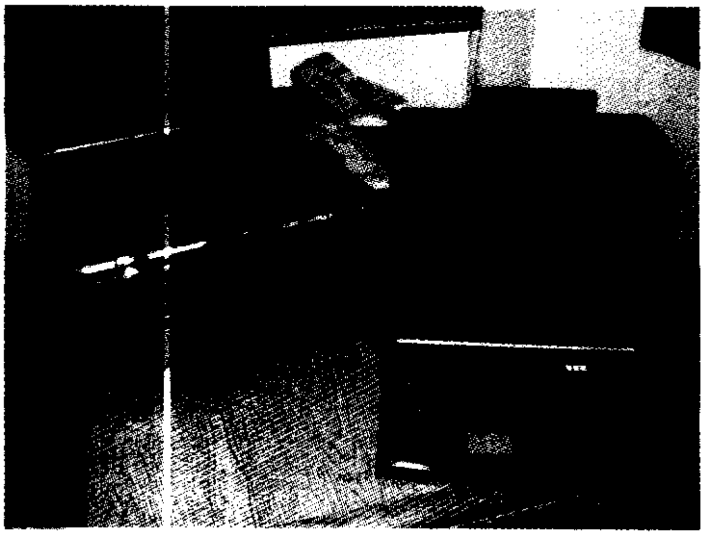

Figure III-3 Portable PC and Carrying Case

Appendix IV. Performance Analysis of Radar Transceiver Unit

The radar transceiver that was studied for potential use is a small unit made by Microwave Device Technology (MDT) in Westford, MA. They manufacture and sell these units, in a variety of configurations, at X-band and at Ka-band, for many commercial applications including police radars. Their uses also include garage or parking lot door operation, perimeter intrusion detection, etc. The configuration that TSC studied is an X-band device having both I and Q video output channels, so that the Doppler-derived direction and speed of a vehicle can be determined. The units can also be equipped with a varactor tuning diode so that the frequency of the transmitter can be swept for FM/CW ranging as proposed.

The transceiver is built inside an aluminum cube about 2" on each side that contains a Gunn device oscillator, and two Schottky barrier diode detectors. The RF connection is WR-90 waveguide. The transceiver weighs about 6 ounces. A very low noise and stable DC power supply is also required at 10 VDC and 0.8 amps to drive the Gunn oscillator, which produces 100 mW of RF power. Also required are low noise video amplifiers connected to the detector outputs to preserve the noise figure. The cost for a large batch (27) of these units is $325 each. The inclusion of varactor tuning may increase the cost somewhat, and TSC will explore this option with the manufacturer.

For application to traffic monitoring TSC proposes to overcome the signal and noise limitations of the Gunn device by using an antenna of much larger size and gain than is usually connected to these transceivers. Performance analysis was carried out by assuming a large antenna diameter and radar cross-section (RCS) for typical vehicles. Using the elementary radar equation, the expected received signal was calculated. This was then compared to the separately derived sources of noise that compete with the received signal to make sure these would not significantly degrade radar operation. These noises are:

1. "Thermal noise"; this will always be the ultimate limiting noise factor, although others may be greater. Independent of received signal amplitude.
2. Diode detector noise; this is a fluctuation noise having the usual "1/f" characteristic at offset (Doppler) frequencies near zero. It results from low frequency bias currents in the diode, from detection of the local oscillator. Independent of received signal amplitude.
3. "Phase noise"; essentially a frequency instability modulation of the Gunn oscillator transmitted signal. The received signal that is backscattered from the moving vehicle target and stationary terrain clutter will have the same fluctuation as the transmitted signal. At very short ranges the noise in the received signal is highly correlated with the local oscillator sample of the transmitted signal. It is therefore strongly canceled in the detector mixing process and is not a problem. At longer ranges it becomes de-correlated and will not cancel as much.

Resolving a target in range with FM/CW radars requires only that the transmit frequency be linearly swept over a range of RF frequencies, and that the detected output signal be processed in a FFT. The range to the target corresponds to the difference frequency that appears in one of the bins of the FFT. The range resolution corresponds to the resolution of the FFT and is dependent on the swept RF bandwidth. To get a range resolution of 10 feet requires a swept bandwidth of 50 MHz. The MDT transceivers are available with varactor tuners which enable electronic tuning over 50 MHz. To simultaneously measure range and Doppler offset requires only that an up sweep in frequency is followed by an equal down sweep. The Doppler and range frequency offsets are separated by both subtracting and adding the total offsets during each of the two sweeps. This is a well known, low risk technique. It is possible that some further performance improvement can be obtained by changing the transceiver to 24 GHz rather than 10 GHz. Ku band units are available from MDT. There are two possible advantages: 1) The antenna would probably be smaller, 2) the Doppler offsets would be 2.4 times as great, which would move further away from the carrier and provide the corresponding improvement in S/N. This option was not fully evaluated during TSC's brief study.

Designing and building mechanical adapters for the tower and installing equipment on the towers is also required. The estimated weights of the various components to be installed on the tower are shown in Table 2 below.

Table V-2

Component	Estimated Weight	Comments
4 foot dish antenna	40 pounds	Includes mounting hardware & radome
1 foot dish antenna	4 pounds	
½ foot horn antenna	2 pounds	
3 radar units	5 pounds	
3" dia. By 7 ft mntg pips	17 pounds	
Mounting hardware	8 pounds	
Total Weight	**78 pounds**	

A drawing of the candidate 4 foot dish antenna is provided in Figure V-1 below. The 4 foot dish antenna will include a radome that extends from the rim of the dish in a conical form to the point of the waveguide feed. The purpose of this is to reduce wind load, as the shape will then have less drag than the bare dish. The dish and its feed are additionally weather proof.

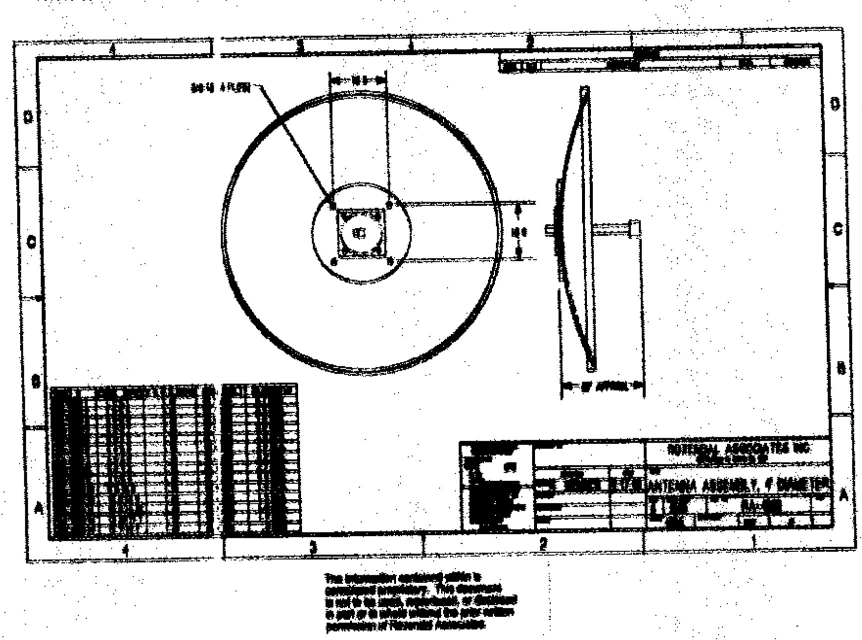

Figure V-1 Dish Antenna

Appendix VI Cost Estimate

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