Innovations Deserving
Exploratory Analysis Programs

*Highway IDEA Program*

# *A New Technique for Characterizing Pavement Surface Profiles and Textures*

Final Report for Highway IDEA Project 62

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TRANSPORTATION RESEARCH BOARD
*OF THE NATIONAL ACADEMIES*

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# TABLE OF CONTENTS



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c. 2

# 1. EXECUTVE SUMMARY

## 1.1. CONCEPT

This project aims to develop a compact, low-cost, high-resolution millimeter-wave sensor and demonstrate its use in real time measurements of surface conditions, including transverse profiles, micro/macro textures, and segregation. Compared to other technologies, millimeter waves have two uniquely distinct characteristics that can be exploited for non-destructive, high-resolution surface measurements: higher frequencies and larger absolute bandwidths. These characteristics together can produce a system that has fine resolution and small size.

## 1.2. SUMMARY

**We completed the design, integration, and test of the millimeter-wave sensor prototype.** The sensor, as shown in Fig. 1, is completely realized using millimeter-wave integrated circuits and is thus compact and low-cost. We achieved very promising results, demonstrating the workability of our system and proving that a surface profile can be accurately mapped.

To prove the surface-profiling concept, we tested the prototype in two laboratory samples. The first sample [Fig. 2(a)] consists of a metal foil deposited on top of a foam block. The measurement was made as the sample was moved across the sensor's antenna. The surface profile was imaged and displayed on a computer screen. The measured contour, as shown in Fig. 2(b), resembles very well the shape of the actual sample. As we moved the sample by hand, an exact comparison between the dimensions of the image and those of the actual sample was not feasible. To compare these dimensions, we would need to move the sample using a conveyor, which must be electronically synchronized with our signal processing. The second sample, as shown in Fig. 3(a), consists of several tiles placed next to each other at different heights. The sensor imaged the tiles as they were moved under the antenna. Fig. 3(b) shows the mapping of the surface profile. As can be seen, the sensor produced a profile well resembling the actual surface. These measured results indicate that we can map a surface with sub-millimeter resolution. To our best knowledge, **this sensor is the first millimeter-wave sensor ever developed and demonstrated for pavement surface mapping**, and its measured results are very promising.

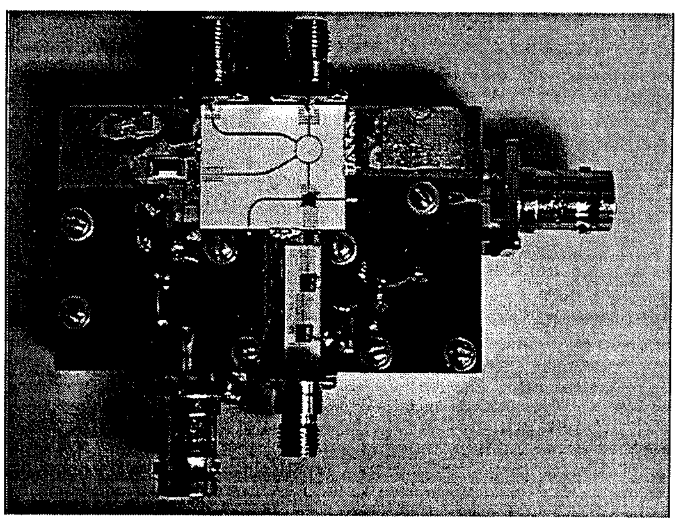
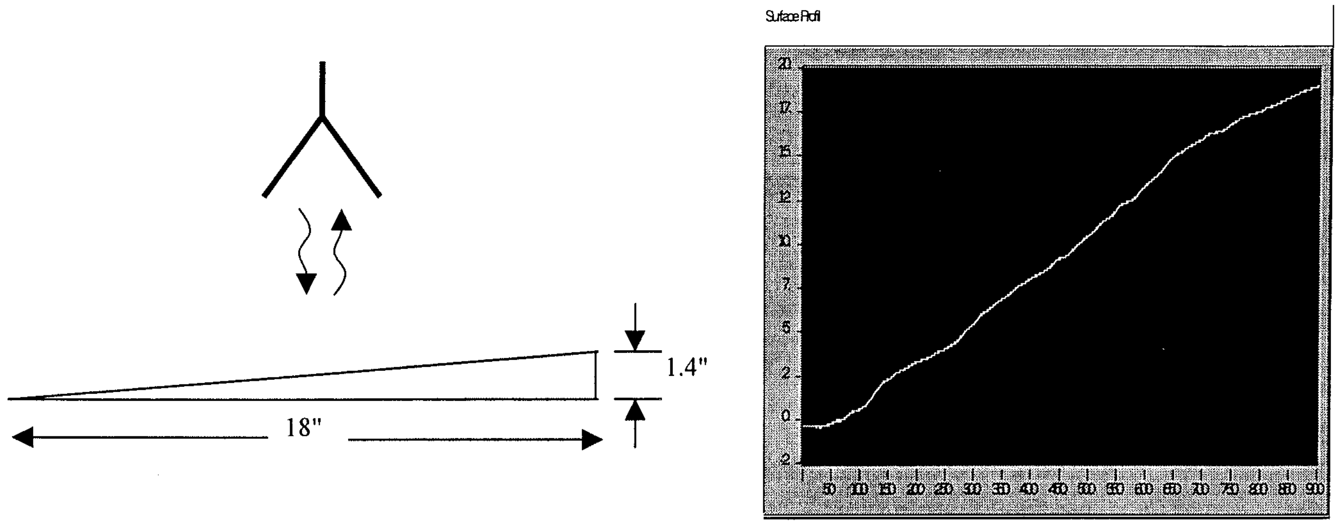
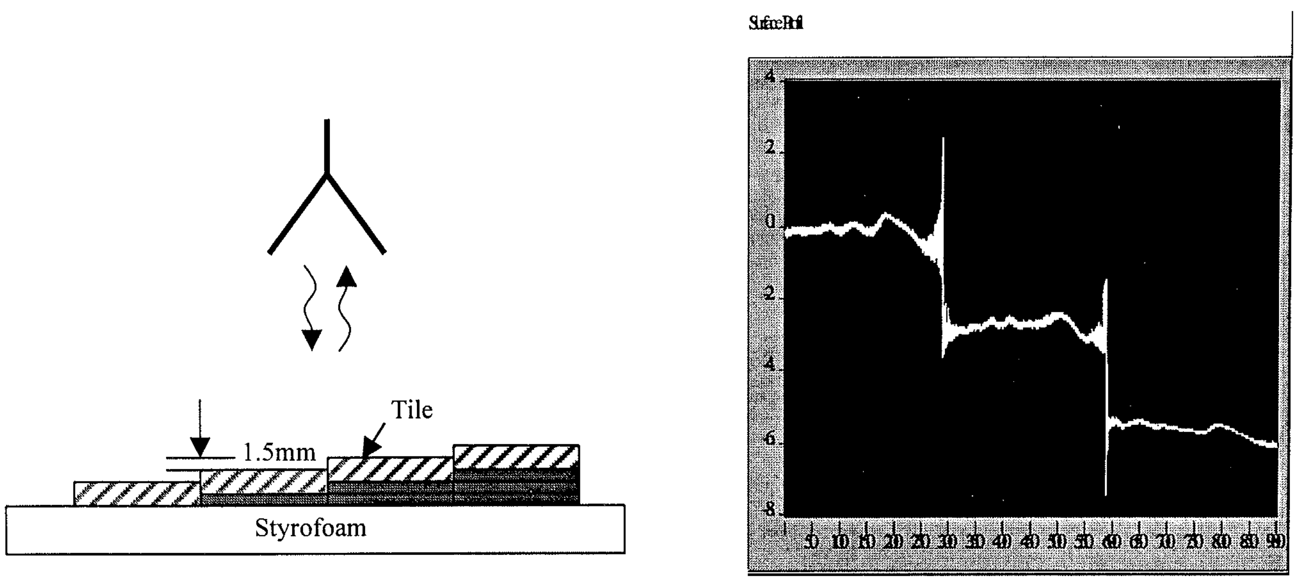


**FIGURE 1 The developed millimeter-wave sensor prototype. Millimeter-wave integrated circuits are used – making the sensor compact and low cost.**




(a) (b)

**FIGURE 2 Sample of metal foil on top of a foam block (a) and the surface mapped by the sensor (b)**




(a) (b)

**FIGURE 3 Sample of several tiles (a) and the surface mapped by the sensor (b).**

The fabricated sensor prototype – although demonstrating that it is possible to accurately map a surface profile and proving our proposed concept – is not yet able to measure precisely pavement surface conditions. The sensor is being redesigned. The antenna used in the fabricated sensor prototype is a waveguide horn antenna having a 3-dB beamwidth of 16 degrees. This antenna has a relatively large beam spot and, thus, does not provide fine cross-range resolution needed for surface mapping. A lens horn antenna having 2-degree beamwidth, which provides smaller beam spot and better resolution, is being considered. Measurements of micro and macro textures on constructed pavement samples will be made with this redesigned sensor and the lens horn antenna.

We constructed several lab specimens, which represent the range of pavements and materials found in the field, to be used in evaluating the sensor. These samples include coarse chip seed (high macro texture and moderate micro texture), polished surface (low macro and micro textures, and poor skid resistance), fine grained surface (low macro texture and high micro texture), tined concrete (high macro and micro textures, and good skid), and segregation.

# 2. BODY

## 2.1. IDEA Product

This project results for the first time a new compact, low-cost millimeter-wave sensor prototype that has new potential capabilities of accurate, real-time measurements of pavement surface conditions - including transverse profiles, micro/macro textures, and segregation.

This millimeter-wave sensor prototype had never been developed and demonstrated for pavement surface mapping. Because of its fine resolution, the developed millimeter-wave sensor prototype is capable of precisely measuring the pavement surface texture. In addition, this is the first time millimeter-wave technology has been implemented for transportation practice, and thus should open up a whole range of new applications, which have not yet been feasible with available technologies.

The sensor developed in this study will be capable of being installed in highway data collection equipment. It will provide critical inputs to Pavement Management Systems in terms of pavement rut depths and skid resistance (from macro/micro). Segregation application will be a valuable tool for checking the quality of newly constructed pavements and new surfacing. Our success in the demonstration of this prototype - proving the concept of using millimeter-wave sensing technology for surface mapping – certainly paves the way for future developments and productions of advanced low-cost millimeter-wave sensors for transportation practice.

## 2.2. Concept and Innovation

The innovation of our developed sensor primarily lies in the use of millimeter waves as a new sensing technique for pavement surface measurements. Millimeter waves, generally referring to the portion of the electromagnetic spectrum between 30 and 300 GHz, have been successfully used for military applications. However, they had not been studied for pavement evaluations. As compared to microwaves (1-30 GHz), millimeter waves operate at higher frequencies, which can be exploited for non-destructive, high-resolution surface texture measurements. The higher frequencies allow one to reduce component size, resulting in compact systems, which are desirable for low-cost and light-weight. Furthermore, narrow beamwidths are inherently achieved, which in turn provide greater resolution of closely spaced objects, higher angle resolution (or cross range) for area mapping, and higher antenna gain leading to with lower peak and average power requirements and better capability of detecting and locating small objects.

Our millimeter-wave sensor prototype is an interferometer realized using millimeter-wave integrated circuits. Interferometor utilizes both the amplitude and phase information of the wave reflected from the pavement surface and is, thus, a very accurate technique for measuring surface profile. The use of millimeter-wave integrated circuits allows the entire system to be realized on microchips. In addition, antenna having high gain and narrow beamwidth is used, leading to enhanced resolution. The new sensor can inspect pavements in real time and at highway speeds, thus not impeding the traffic flow. Altogether, our developed sensor prototype offers unique characteristics of small size, low cost, simplicity, fast, fine resolution and high surface-measurement accuracy, which is attractive for practical transportation applications.

## 2.3. Investigation

Four tasks were performed in this project. They are described as follows.

### *2.3.1 Task 1 – Construction of Laboratory Samples*

We constructed several lab specimens, which represent the range of pavements and materials found in the field. Figs. 4 to 7 show these samples covering different macro and micro textures.

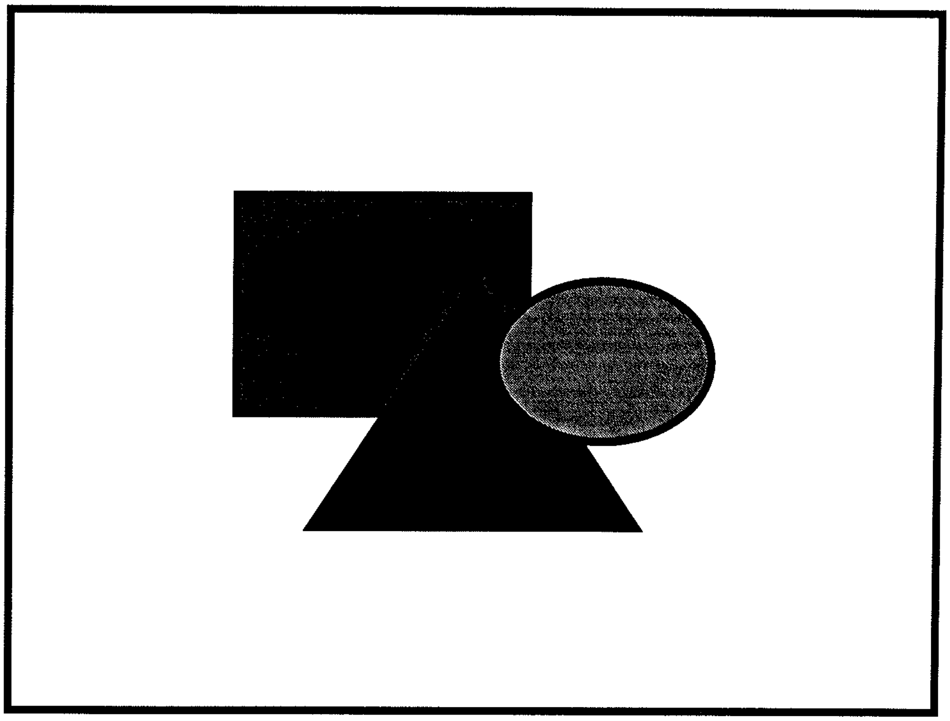


FIGURE 4 Coarse chip seed (high macro texture and moderate micro texture).

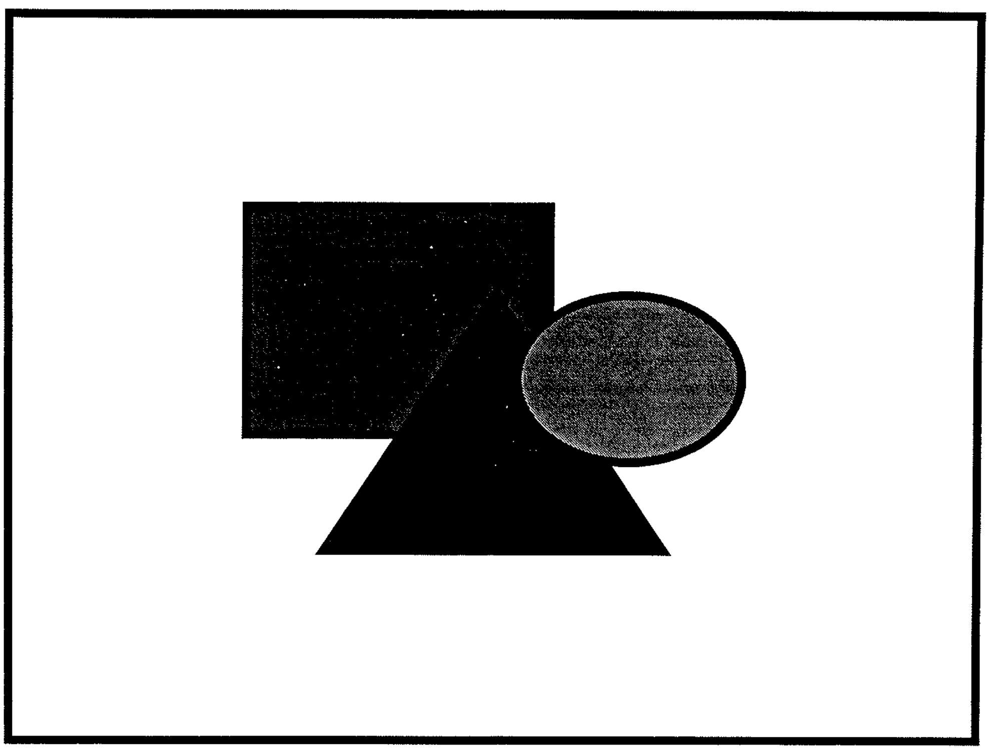


FIGURE 5 Polished surface (low macro and micro textures, and poor skid resistance).

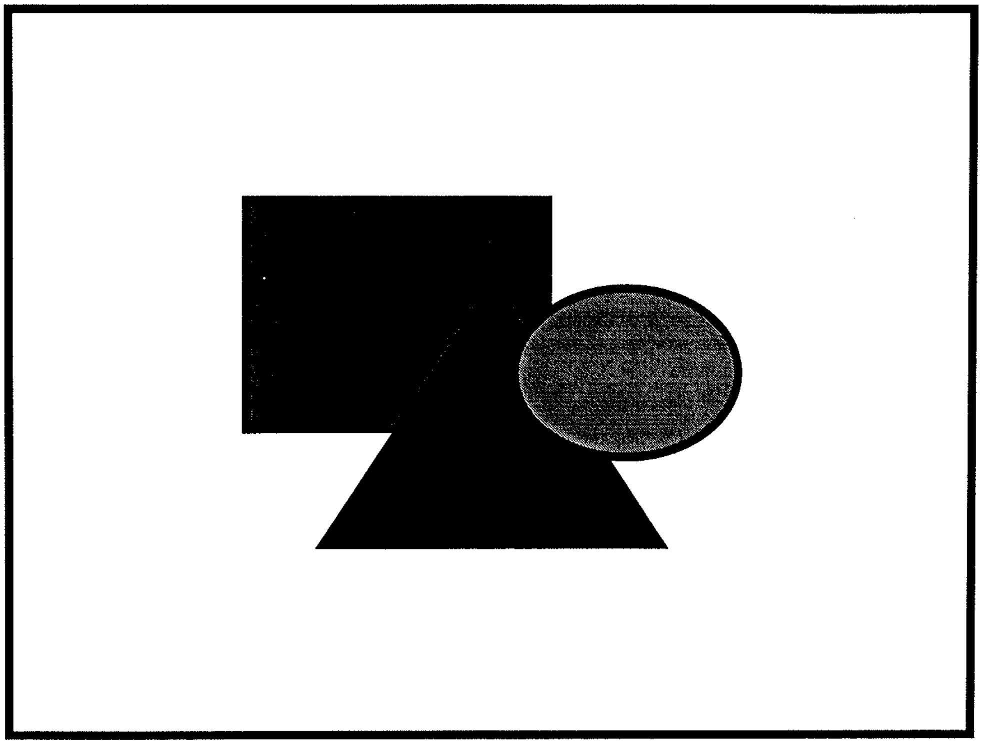


FIGURE 6 Fine grained surface (low macro texture and high micro texture).

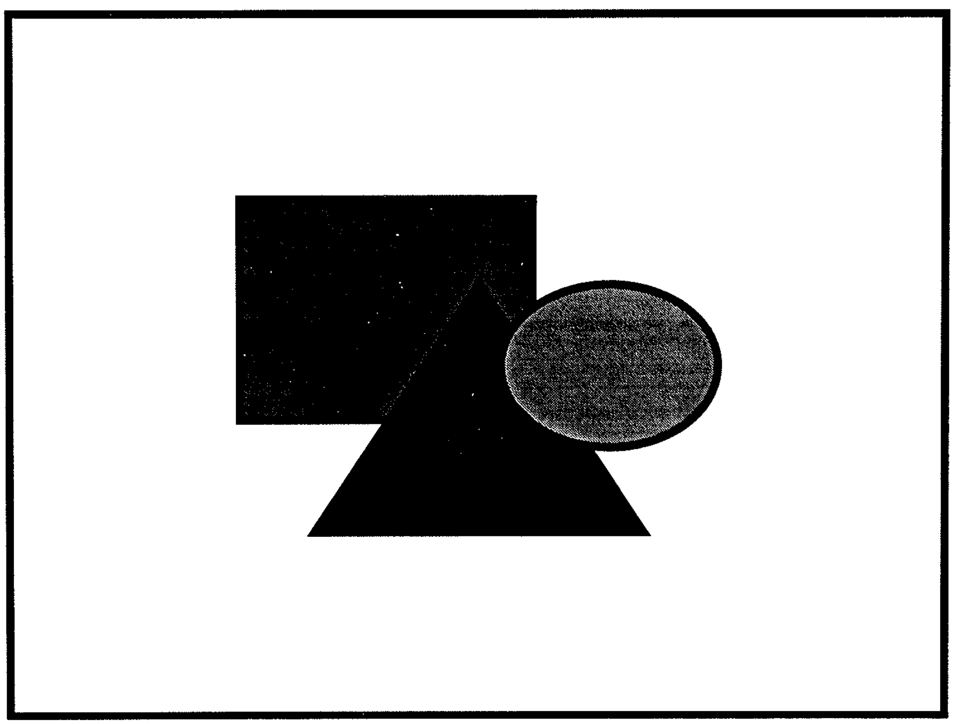


FIGURE 7 Tined concrete (high macro and micro textures, and good skid).

*2.3.2 Task 2 – Development of the Millimeter-Wave Sensor*

We investigated several millimeter-wave system configurations and decided to use an interferometer system due to its high measurement accuracy and fast operation. We conducted a theoretical investigation of the millimeter-wave interferometer for characterizing pavement surface roughness. Our simulations demonstrated that it is possible to characterize pavement surface roughness using the millimeter-wave interferometer technique. Our measurement results confirm this sensing approach.

2.3.2.1 System Description

Fig. 8 shows the schematic of the millimeter-wave sensor with major components. The transmitter generates a millimeter-wave signal to illuminate the pavement via an antenna. The receiver captures the return signal from the pavement via an antenna and converts it into a base-band signal, which is then processed to produce the pavement surface profile.

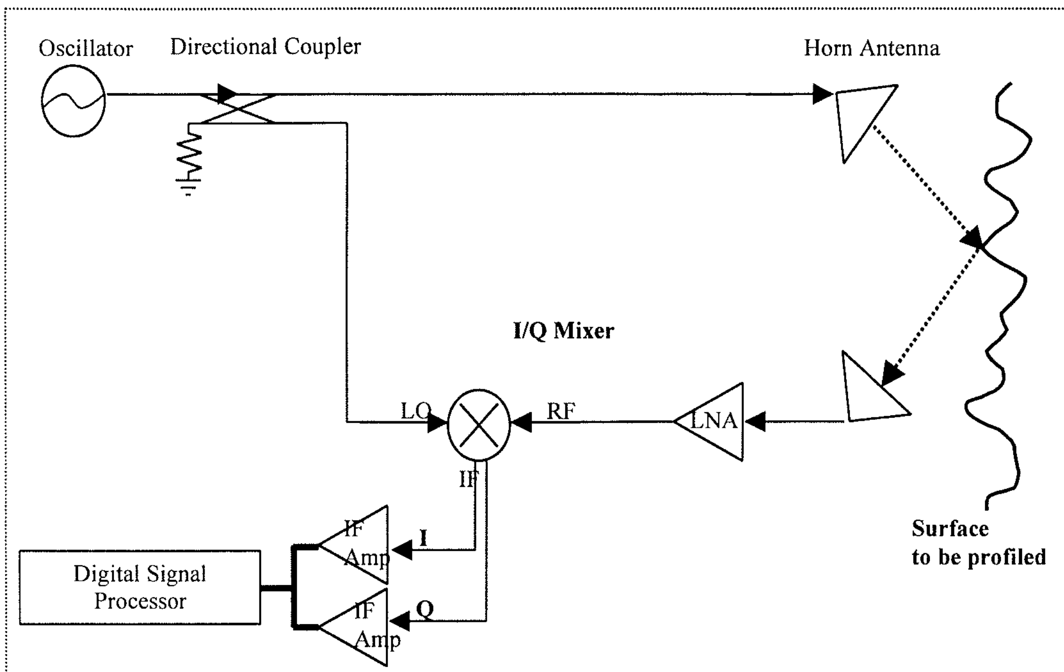



**FIGURE 8 Schematic of the millimeter-wave sensor (some components are not shown).**

2.3.2.2 System Design and Fabrication

We completed the design, fabrication, and test of many components needed for the millimeter-wave sensor using a soft substrate (Duroid 5880). To support this activity, we had to purchase a bonding machine using our internal funds. The cost of this machine ($18,000) was not anticipated and thus not included in the project's budget. We also completed the layout and fabrication of the entire sensor on a single board using the soft substrate. However, we encountered many problems in the sensor integration process. The microwave monolithic integrated circuits (MMICs) failed to be attached to the board using the bonding machine. Although bonding onto a soft substrate can be done – as has been successfully done in industries - we found that it is very difficult and not suitable for students who do not have much experience in this assembly process. For better and reliable bonding, we concluded that we must use a hard substrate for the sensor.

To avoid the problems caused by the soft substrate described above, we completely redesigned all the circuits needed for the sensor using a (hard) alumina substrate. Fabrication of these sensor circuits was completed by an outside processing foundry. We completed the design of the sensor test fixtures, prepared the system layout (Fig. 9), and assembled the sensor. In this assembly process, we successfully placed all the tiny MMIC chips and the alumina circuits on the aluminum test fixture, which houses the sensor, and successfully bonded these chips and alumina circuits together using the bonding machine. Fig. 1 shows the complete assembled sensor. During the assembly process, several MMIC chips were damaged and replaced. Some of these damages were not found during the assembly since the chips are too small – they were discovered only when we tested the system. Sometimes, replacing the damaged chips caused the damage to the other chips, which further complicated the problem. Please note that damage of MMIC chips during an assembly process is not unusual as the processing requires several steps (epoxy, curing, bonding, etc.), and many times one has to repeat these steps for several chips on the same system. Even highly skilled technicians in industries damage these chips during assembly. Because of the long assembly process by students and the need of processing circuits from an outside company, there was an inevitable delay in the project. Nevertheless, **we have successfully assembled the millimeter-wave sensor prototype**. Several tests were conducted to prove the system concept for surface measurement, as described in Sections 1.1 and 2.3.4.

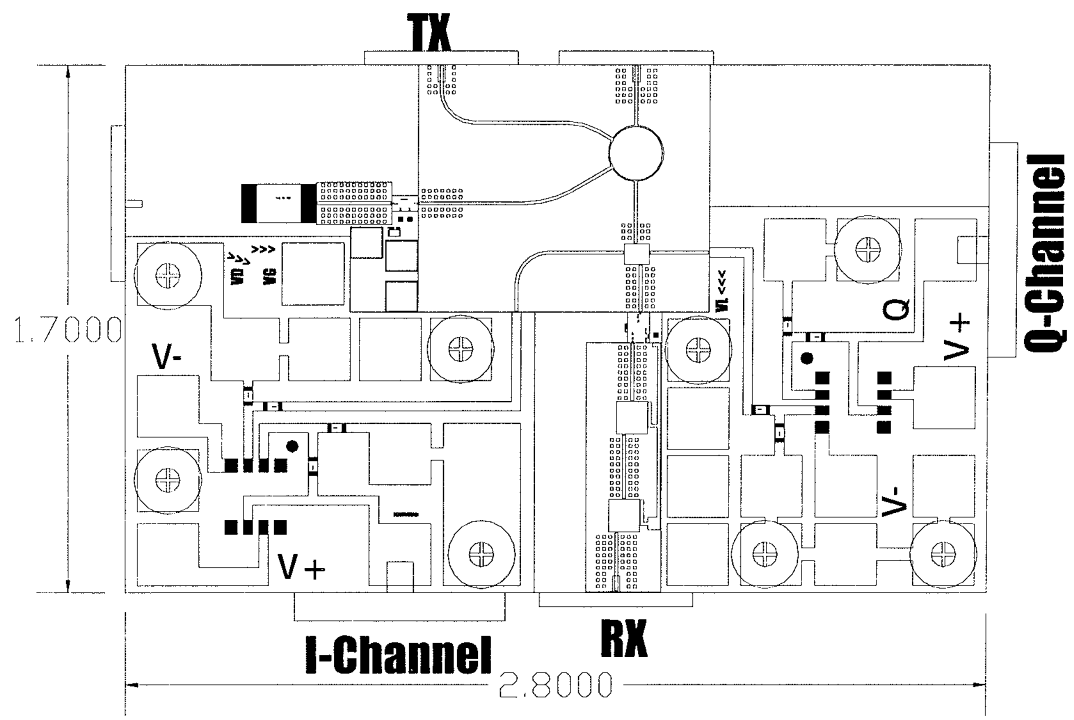



**FIGURE 9 Layout of the millimeter-wave sensor (Unit: inch).**

The sensor is being redesigned. The antenna used in the sensor prototype is a waveguide horn antenna having a 3-dB beamwidth of 16 degrees. This antenna has a relatively large beam spot and, thus, does not provide fine cross-range resolution needed for surface mapping. A lens horn antenna having 2-degree beamwidth, which provides smaller beam spot and better resolution, is being considered. Measurements of micro and macro textures on constructed pavement samples will be made with this redesigned sensor and the lens horn antenna.

*2.3.3 Task 3 – Development of Signal Processing for the Millimeter-Wave Sensor*

The millimeter-wave sensor constructs a pavement surface profile using the phase difference between the signals transmitted to and received from the pavement surface. A signal-processing algorithm is needed to perform this task. To facilitate this purpose, we have analyzed the phase error due to the imbalance between the I and Q channels of the I/Q mixer used in the sensor's receiver. We have also developed a preliminary signal-processing algorithm based on the phase unwrapping technique. This special signal-processing algorithm is needed for our sensor. Conventional signal processing software for ground penetrating radar, such as the one we developed at Texas Transportation Institute, is not suitable for this sensor.

2.3.3.1 Analysis of Phase Error Due to I/Q Mixer Imbalance

The I/Q mixer in the sensor's receiver detects the phase change between the transmitted and received signals. This phase difference is then used to construct the pavement surface profile. It is thus critical to measure this phase accurately and compensate for any error caused by the I/Q mixer imbalance. This phase is obtained as

$$\phi(t) = \tan^{-1}\left(\frac{V_I(t)}{V_Q(t)}\right) \quad (1)$$

where

$$\begin{aligned} V_I(t) &= \frac{(V_{RF} + \Delta V_{RF})(V_{LO} + \Delta V_{LO})}{2}\sin[\phi_o(t) + \Delta\phi_{RF} + \Delta\phi_{LO}] + V_{I,off} \\ V_Q(t) &= \frac{V_{RF}V_{LO}}{2}\cos\phi_o(t) + V_{Q,off} \end{aligned} \quad (2)$$

$V_I(t)$ and $V_Q(t)$ are the in-phase and quadrature output voltages of the I/Q mixer, respectively. $\Delta V_{RF}$, $\Delta \phi_{RF}$ and $\Delta V_{LO}$, $\Delta \phi_{LO}$ are the amplitude, phase imbalance of the RF and LO signals applied to the I/Q mixer, respectively. $V_{I,off}$ and $V_{Q,off}$ are the offset voltages of the in-phase and quadrature outputs of the I/Q Mixer. $\phi_o(t)$ represents the phase measured by an ideal I/Q mixer (i.e., without amplitude and phase imbalance).

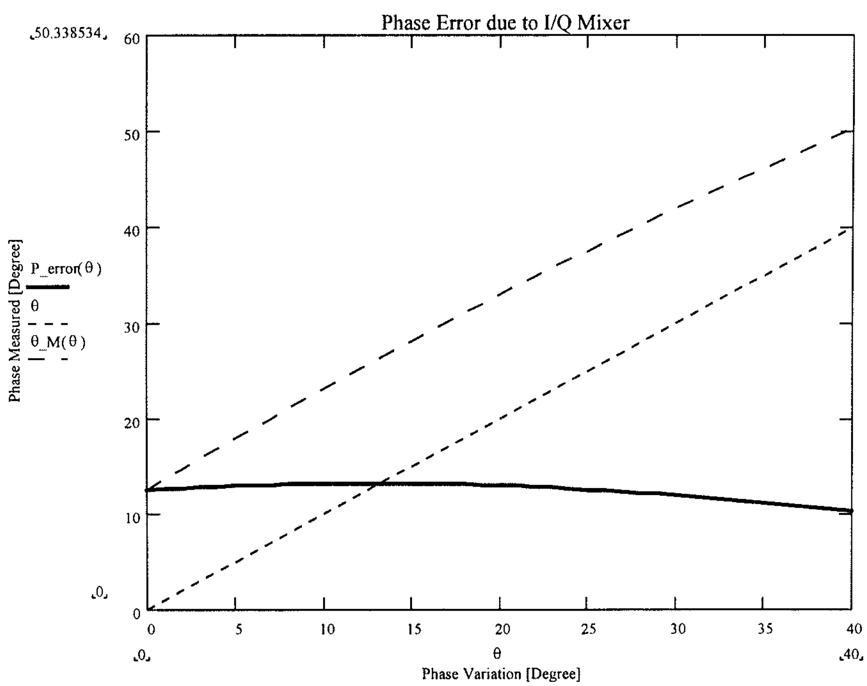



**FIGURE 10 Phase error estimation.**

Fig. 10 shows the phase calculations assuming 5-deg phase imbalance and 10-percent amplitude imbalance for the RF and LO signals. The dotted line shows the measured phase versus the phase variation (i.e., the theoretical phase) when the

I/Q mixer is completely balanced. The dashed line shows the measured phase taking into account the I/Q mixer imbalance. The solid line shows the phase error between the theoretical and measured phases caused by the I/Q mixer imbalance. In practical systems, the phase error cannot be avoided, thus causing potential errors in measuring a surface profile. To eliminate or minimize this source or error, we must measure the amplitude and phase unbalances of the I/Q mixer and compensate for them in the signal-processing algorithm.

### 2.3.3.2 Phase-Unwrapping Signal-Processing Technique

In our millimeter-wave sensor, the phase data produced by the I/Q mixer is wrapped into the range [-π, π]. The phase-unwrapping technique is used to reconstruct the wrapped phase beyond the range of [-π, π]. Mathematically, the phase unwrapping operation is described by the following equation in the discrete time domain:

$$\Phi(n) = \varphi(n) + 2\pi k(n) \qquad (3)$$

where φ(n) is the unwrapped phase, which is the quantity we need to detect, and k(n) is an integer function that excutes the wrapping of φ(n).

We introduce two operators W and Δ. The operator W wraps the phase into the range [-π, π] as

$$W\{\varphi(n)\} = \Phi(n) + 2\pi k(n), \qquad n = 0, 1, \quad \ldots \quad , N-1 \qquad (4)$$

The difference operator Δ is defined as

$$\begin{aligned} \Delta\{\varphi(n)\} &= \varphi(n+1) - \varphi(n) \\ \Delta\{k(n)\} &= k(n+1) - k(n) \qquad n = 0, 1, \ \ldots \ , N-1 \end{aligned} \qquad (5)$$

Applying the wrapping and differentiation to the wrapped phase sequences, we get

$$\Delta\{W\{\varphi(n)\}\} = \Delta\{\varphi(n)\} + 2\pi\Delta\{k_1(n)\} \qquad (6)$$

Applying the wrapping operation again to Eq. (6) yields

$$W\{\Delta\{W\{\varphi(n)\}\}\} = \Delta\{\varphi(n)\} + 2\pi[\Delta\{k_1(n)\} + k_2(n)] \qquad (7)$$

which implies that $\Delta\{k_1(n)\} + k_2(n)$ should be zero to satisfy the requirement of $-\pi < \Delta\{\varphi(n)\} \leq \pi$. Eq. (7) can thus be reduced to

$$W\{\Delta\{\Phi(n)\}\} = \Delta\{\varphi(n)\} \qquad (8)$$

Using Eq. (8), we can show that

$$\varphi(m) = \varphi(0) + \sum_{n=0}^{m-1} W\{\Delta\{W\{\varphi(n)\}\}\} \qquad (9)$$

Eq. (9) indicates that the actual phase sequences can be unwrapped by an iterative operation of the wrapped difference of the wrapped phases.

As a demonstration, we show in Fig. 11 a reconstruction of the following sinusoidal phase sequence

$$\varphi(n) = 5\pi \sin(2\pi f n) \qquad (10)$$

using the phase unwrapping technique. f indicates the periodicity of the surface profile change which may comes from an undulating surface topography. The reconstructed or unwrapped phase (O) and the original phase (solid line) from Eq. (10) match exactly, which implies that the phase, and hence the surface profile, can be reconstructed accurately from the phase produced by the I/Q mixer. The wrapped phase sequence is designated by ×.

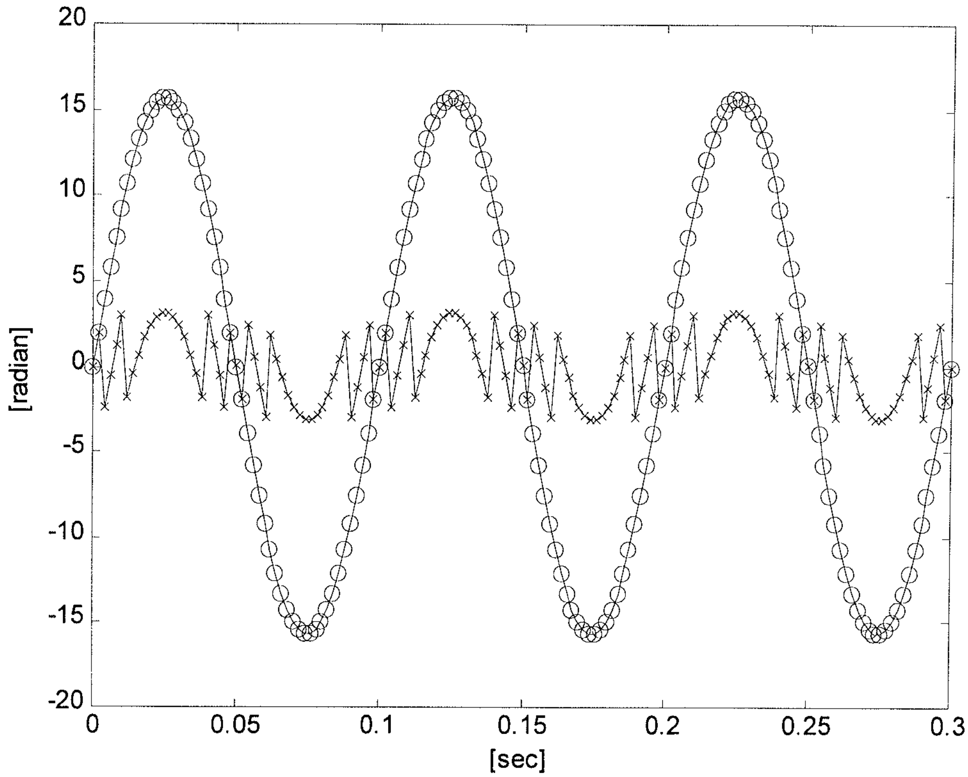



**FIGURE 11 Reconstruction of a sinusoidal phase using the phase unwrapping technique.**

### *2.3.4 Task 4 – System Test and Evaluation*

We completed testing the developed millimeter-wave sensor prototype to demonstrate its proof-of-concept for surface profiling. To that end, we tested the prototype in two laboratory samples. The first sample [Fig. 2(a)] consists of a metal foil deposited on top of a foam block. The measurement was made as the sample was moved across the sensor's antenna. The antenna is a waveguide horn antenna having a 3-dB beamwidth of 16 degrees. This antenna has a relatively large beam spot and, thus, does not provide fine cross-range resolution needed for surface mapping. The surface profile was imaged and displayed on a computer screen. The measured contour, as shown in Fig. 2(b), resembles very well the shape of the actual sample. As we moved the sample by hand, an exact comparison between the dimensions of the image and those of the actual sample was not feasible. To compare these dimensions, we would need to move the sample using a conveyor, which must be electronically synchronized with our signal processing. The second sample, as shown in Fig. 3(a), consists of several tiles placed next to each other at different heights. The sensor imaged the tiles as they were moved under the antenna. Fig. 3(b) shows the mapping of the surface profile. As can be seen, the sensor produced a profile well resembling the actual surface. These measured results indicate that we can map a surface with sub-millimeter resolution.

### 2.4. Plans for Implementation

**The first millimeter-wave sensor prototype has been built and tested to prove the surface-mapping concept. The measured results demonstrated its potential as an effective tool for real-time measurement of pavement surface**

**conditions**. The sensor is being redesigned and a new lens horn antenna with much smaller beam spot is being considered for the sensor. We will carry out the following plans for potential implementation of the new millimeter-wave sensor for transportation practice:

#### *2.4.1 Task 1 – Laboratory Test and Evaluation*

Complete the redesign and fabrication of the millimeter-wave sensor prototype, acquire the lens horn antenna, and perform laboratory test and evaluation for the sensor on the pavement samples constructed in Task 1. A conveyor also needs to be purchased and electronically synchronized with our signal processing to facilitate these tests.

#### *2.4.2 Task 2 – Field Test and Evaluation*

Perform field test and evaluation of the redesigned sensor. Texas Transportation Institute (TTI) has a National Skid Resistance test site at the Texas A&M University's Riverside Campus and a recently constructed roughness calibration facility. These are actual pavement sections with either known surface characteristics or known rut depths. As a first step, the sensor will be used at the National Skid Resistance test site to monitor the texture of the skid pads. This will give a direct comparison between the surface texture and the known skid resistance value. The sensor will then be used for surface measurements at the TTI's roughness calibration facility. It is also proposed to take the sensor to several recently completed hot mix jobs to scan for possible segregation. If anomalous readings of texture are encountered, cores will be taken of the highway to validate if that area has any significant segregation. This is quantified as a change in aggregate gradation

#### *2.4.3 Task 3 – Signal Processing*

We have developed a preliminary signal processing algorithm for surface mapping using the phase unwrapping technique (see Section 2.3.3). This signal processing technique has proved to be able to map the surface profile. It should be noted that our sensor – based on the interferometry technique – constructs a pavement surface profile using the phase difference between the signals transmitted to and received from the pavement surface. A special signal-processing algorithm, such as the phase unwrapping technique that we have been developing, is needed to perform this task. Conventional signal processing software for ground penetrating radar, such as the one we have developed at TTI, is not suitable for this application. We propose to complete this phase-unwrapping signal processing tool as it is needed for the developed sensor.

#### *2.4.4 Task 4 – Product Transfer*

Texas Transportation Institute (TTI) at the Texas A&M University is working closely with the states of Florida, Texas, and North Carolina in implementing advanced technologies for pavement applications. These states, as well as others, are likely potential users of the proposed millimeter-wave system once it is developed, and serve as the bases for transfer the results to transportation practice. Toward the objective of transferring the results to practice, we propose to demonstrate the new millimeter-wave sensor prototype to these organizations as well as other states' DoT. We will then work with them to implement the results for transportation practice.

## 3. CONCLUSIONS

Texture and transverse profile measurements of highway surfaces are critical for highway safety. It is the texture, which provides skid resistance and the transverse profile that dictates surface drainage. Currently, highway agencies can not measure these properties in real time.

This project has produced, for the first time, a new low-cost, compact millimeter-wave surface-profiling sensor prototype and demonstrated its potential for fast and accurate measurement of pavement surface conditions in real time, including transverse profiles, micro and macro textures, and segregation. The new sensor is capable of being installed in highway data collection equipment and can inspect surface at highway speeds, thus not impeding the traffic flow. It will provide critical inputs to Pavement Management Systems in terms of pavement rut depths and skid resistance (from macro/micro texture). For segregation application, the new sensor will be a valuable tool for checking the quality of newly constructed pavements and new surfacing. The new millimeter-wave sensor had not been studied and developed for transportation applications. It thus has great potential for transportation practice – particularly, in mapping pavement surface conditions. This new millimeter-wave sensing technique potentially expands the knowledge base of the transportation community and contributes significant sensing breakthroughs for transportation practice. Specifically, it will have a major impact on both safety and new construction quality control. It will also pave the way for future research and developments of advanced low-cost millimeter-wave sensors for transportation practice.

In order to achieve the implementation the project results for transportation practice, we propose to perform the plans outlined in Section 4 (Plans for Implementation).

## 4. INVESTIGATOR PROFILES

Dr. Cam Nguyen and Mr. Tom Scullion are the principal and co-principal investigators of this project, respectively.

### 4.1. Cam Nguyen

Dr. Nguyen joined the Department of Electrical Engineering at Texas A&M University in 1991, where he is now a Professor and Director of the Sensing, Imaging and Communications Systems Laboratory. He had held various engineering positions in industry from 1979-1991. He was a Microwave Engineer with ITT Gilfillan Co., a Member of Technical Staff with Hughes Aircraft Co., a Technical Specialist with Aerojet ElectroSystems Co. – all in California – a Member of Professional Staff with Martin Marietta Co. in Florida, and a Senior Staff Engineer and Program Manager at TRW in California. While in industry, he led and played a crucial role in the technical leadership of various microwave and millimeter-wave R&D and technology projects. He also developed many MIC and MMIC components and subsystems up to 220 GHz for radar, remote sensing, and communications applications.

Dr. Nguyen has made significant contributions in teaching and research in various areas of microwave and millimeter-wave electronics. He has developed and taught different courses in microwaves – from theoretical field analysis to practical design of microwave ICs and systems. He has established and led a diversified and interdisciplinary research using microwave and millimeter-wave technologies. His current research interests encompass both the theoretical and practical aspects of RF, microwaves, millimeter-waves, and electromagnetic, with concentration on the research and developments of novel RF, microwave and millimeter-wave ICs, UWB components, receivers, transmitters, sensors, radars, and subsurface and surface sensing technologies for various engineering applications. His research activities have resulted in many novel microwave and millimeter-wave ICs and systems – contributing to the advances of microwave engineering.

Dr. Nguyen has published more than 110 refereed papers, one book and several book chapters, and edited three books. He is a Registered Professional Engineer of the State of Texas, a senior member of the IEEE, Microwave Theory and Techniques and Antenna and Propagation Societies, and a member of Commission D of URSI. He is listed in Who's Who in the West, Who's Who in the South and Southwest, Who's Who in America, Who's Who of Emerging Leaders in America, Who's Who in Science and Engineering, and Who's Who Among Asian Americans. He is a member of the editorial board and technical committees, and a reviewer for various journals and conferences, such as the IEEE Transactions on Microwave Theory and Techniques, IEEE Transactions on Magnetics, IEEE Microwave and Wireless Components Letters, IEEE Transactions on Antennas and Propagation, IEE Proceedings on Microwaves, Antennas and Propagation, IEE Electronics Letters, and Microwave and Optical Technology Letters.

Dr. Nguyen is the Chairman of the annual International Conference on Subsurface and Surface Sensing and Imaging Technologies and Applications, Editor-in-Chief of Subsurface Sensing Technologies and Applications: An International Journal, and Editor of the Subsurface and Surface Sensing International Book Series, published by Kluwer Academic/Plenum Publishers.

### 4.2. Tom Scullion

Tom Scullion holds a B.S. in Physics and Mathematics, an M.S. in Material Science, and an MBA. He has 20 years of experience in highway and pavement research, and non-destructive testing.

From 1975 to 1980, he was a research officer at National Institute of Transportation and Road Research, Pretoria, South Africa, conducting research in pavement. Since joining Texas Transportation Institute in 1980, he has been actively involved in highway research, pavement rehabilitation, instrumentation, non-destructive testing and information system development and implementation. He is program manager of the Pavement Systems Program at TTI. Currently he is principal investigator on the development of a Pavement Management System for the State of Texas. This is a large project aimed at upgrading the Texas system to comply with the Federal mandate which takes effect in 1993. He has been the principal investigator on several major pavement instrumentation projects, including projects completed for the Federal Highways Administration, Corps of Engineers and North Carolina State University, as well as Texas DOT. Mr. Scullion is currently principal investigator on two major GPR projects. He is also co-principal investigator on SHRP project H104 which is developing a new high frequency radar system specifically for pavement evaluation.

Mr. Scullion has developed signal processing software for GPR interpretation and has pioneered the application of GPR for transportation applications in Texas. He has demonstrated the accuracy of using GPR for layer thickness measurements and has worked closely with Texas DOT personnel in using GPR on several major multimillion dollar rehabilitation projects. He has also established a GPR laboratory at TTI which has the capability of both field and laboratory testing.

Mr. Scullion has a solid working relationship with the Texas DOT and has completed several major forensic investigation to identify causes of pavement failure. By combining advanced non-destructive testing results he has successfully identified problems with flexible, jointed and continuously reinforced concrete pavements in Texas. He is currently assisting TxDOT with the implementation of the MODULUS backcalculation procedure into their project level pavement design system.

Mr. Scullion is an active member of the Transportation Research Board where he serves on Committee A2B05 "Strength and Deformation of Materials," a member of the SHRP Expert Task Group on Pavement Instrumentation. He also served as a consultant to NAPA on pavement performance, Metro Systems on traffic data collection system design, and World Bank on pavement management systems, and is a registered professional engineer in the state of Texas. Mr. Scullion was a workshop coordinator for the 2nd International Conference on Managing Pavements. He has published more than 40 articles and reports in GPR and highway-related areas.