REPLICATION OF VTI's STATIONARY LASER PROFILOMETER FOR MEASURING ROAD SURFACE PROFILES

Transfund New Zealand Research Report No. 84

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AN IMPORTANT NOTE FOR THE READER

The research detailed in this report was commissioned by Transit New Zealand when it had responsibility for funding roading in New Zealand. This funding is now the responsibility of Transfund New Zealand.

CONTENTS

ABBREVIATIONS

ARRB	=	Australian Road Research Board
ERNL	=	estimated road noise level (dB)
ETD	=	estimated texture depth (mm)
IFI	=	international friction index
ISO	=	International Standards Organisation
LCPC	=	Laboratoire Central des Ponts et Chaussées (French Road Research Laboratories)
L_{ma}	=	macrotexture level (dB)
L_{me}	=	megatexture level (dB)
MPD	=	mean profile depth (mm)
MTD	=	mean texture depth (mm)
PIARC	=	Permanent International Association of Road Congresses
RMS	=	root mean square (mm)
T_{dma}	=	texture depth macrotexture (mm)
TRRL	=	Transport and Road Research Laboratory (now known as TRL - Transport Research Laboratory, England)
VTI	=	Väg-och Trafik-Institutet (Swedish Road and Traffic Research Institute)

EXECUTIVE SUMMARY

Introduction
The development (including design and operation) of a portable stationary laser profilometer and the associated analysis software is described. The instrument was developed and tested (during 1996) for measuring surface texture profiles of New Zealand roads to a higher resolution than is typically possible with vehicle-based systems.

It has similar characteristics to the stationary laser profilometer operated by the Swedish Road and Traffic Research Institute (VTI), and the mobile laser profilometer which was selected as the reference texture measuring instrument for the International PIARC Experiment.

Description
The instrument essentially consists of a laser device which measures the height of the surface below it, using a 0.5 mm diameter laser light spot. The laser device travels along a rail, and so provides a precise vertical cross-section of the surface. The surface height is measured to within an accuracy of ±0.03 mm.

Capability
The new instrument provides the facility to carry out detailed analysis of road surface texture over the wavelength range of 0.63 mm and 500 mm. The height measurement range is to a maximum of 32 mm, and the length measurement range is to a maximum of 1.7 m. The instrument operates quickly and efficiently: a survey of a 200 m site (11 locations at 20 m intervals) can be completed within 2 hours, including data analysis. Software developed for the analysis of the laser profilometer measurements provides a two-page printout of a range of different measurement results, including the mean profile depth (MPD) analysis to ISO Standard 13473-1.

Use of Instrument
The profilometer will be used in detailed investigations of surface texture characteristics of New Zealand pavement types, and also comparative evaluations of texture measurements made with new generation instruments such as the TRRL mini-texture meter and the ARRB profilometer. Measures of texture include mean profile depth, root mean square texture depth, texture profile, and texture wavelength spectra.

Commissioning of Instrument
Development of the Transit New Zealand laser profilometer has been completed to a satisfactory standard, and it is now available for on-site surface texture measurement and analysis.

Recommendations

The following recommendations are made for further development of the instrument to improve its accuracy and ease of operation:

- *Measurement of the Golden Speed constant (Sp)*
  The laser profilometer should be further developed to provide a measurement of the golden speed constant (Sp). The calculated Sp should be calibrated against Sp measurements obtained using equipment which was used in the International PIARC Experiment.

- *Distance measurements*
  An accurate horizontal distance measurement should be incorporated into the analysis, so that the traverse speed no longer needs to be precisely constant.

- *Height measurements*
  Height measurements should be made at the reduced interval of less than 0.1 mm, instead of the interval of 0.3 mm used at present. This reduced spatial sampling interval can be achieved by either increasing the sampling rate or reducing the traverse speed.

- *Laser equipment*
  Although laser camera technology has been improved, quantification of road microtexture, i.e. road profile wavelengths less than 0.1 mm, which is known to directly affect skid resistance and tyre wear, is still not possible. Accordingly, the existing laser equipment should not be replaced with new generation 64 kHz lasers at this point in time.

ABSTRACT

The development and testing, during 1996, of a portable stationary laser profilometer and the associated analysis software is described. The instrument was developed and tested for measuring surface texture profiles of New Zealand roads to a higher resolution than is typically possible with vehicle-based systems.

The instrument is similar to that which has previously been designed and developed by the Swedish Road and Traffic Research Institute (VTI). The Transit New Zealand laser profilometer provides the facility to carry out detailed analysis of road surface texture over the wavelength range of 0.63 mm and 500 mm. The height measurement range of the equipment is to a maximum of 32 mm, and the length measurement range is to a maximum of 1.7 m.

1. INTRODUCTION

Stage 1 of this research project attempted to identify the most appropriate measurement systems for the geometric characterisation of pavement surface texture over the wavelengths associated with microtexture, macrotexture, megatexture and longitudinal evenness. It included a comprehensive literature search as well as corresponding with appropriate equipment manufacturers and overseas research organisations involved with pavement-related work. They included ARRB, LCPC, TRRL and VTI (Cenek 1996).

Stage 1 (reported in Cenek 1996) established that both Australia and New Zealand have lacked the capability to carry out detailed analysis of surface texture over the wavelength range between 0.5 mm and 500 mm. Yet this level of texture directly influences tyre rolling resistance (affecting fuel and oil costs), crashes (medium to high speed skid resistance, spray generation), and tyre noise generation. The stationary laser profilometer system developed by the Swedish Road and Traffic Research Institute (VTI) has been the only instrument which is capable of giving a comprehensive quantification of road macrotexture and megatexture, and which approaches the appropriate microtexture range. Furthermore, in recognition of these unique capabilities, VTI's mobile laser profilometer was selected as the reference texture measuring instrument for the International PIARC Experiment to compare and harmonise texture and skid resistance measurement (PIARC 1995).

The texture spectra which can be generated from the output of the stationary laser profilometer are viewed as a critical element in existing and potential research programmes associated with:

- investigations of macrotexture influence on skid resistance (speed/vehicle influence);
- investigations of changes in macrotexture caused by traffic loading; and
- evaluation of road construction practices.

In consequence the conclusion of the Stage 1 study was that the VTI stationary laser profilometer should be replicated for use on New Zealand roads. This report describes the development of the New Zealand version of this instrument, an integral component of which is the Selcom laser camera, already owned by Transit New Zealand, and the associated analysis software.

2. OBJECTIVES AND RESEARCH TASKS

The stated objectives and research tasks (in italics) for this project have been achieved in full and any variations are noted as comments in the following sections.

2.1 Objectives

The objectives of Stage 2 of this study are to:

1. *Replicate the VTI stationary laser profilometer; and*
2. *Develop associated data acquisition and signal processing systems for generating third octave band spectra of road surface texture over a wavelength range between 0.5 mm and 500 mm.*

Comment

The analysis presents third octave band spectral levels for the range 0.63 mm to 500 mm. However, as the laser spot diameter is 0.5 mm, no information can be measured for wavelengths less than 0.5 mm, and also some loss of definition is observed for wavelengths below about 2.5 mm.

For the long wavelengths, above 200 mm, the measurements from several consecutive lengths of road profile need to be averaged in order to obtain accurate spectral level measurements for a surface that has consistent texture and profile properties.

Note that only data for wavelengths in the range 2.5 mm to 100 mm are used for the measurement of mean profile depth, as defined by ISO 13473-1 (ISO 1996).

Compared to the VTI stationary laser profilometer fitted with macroprobe, the main improvements incorporated in the Transit New Zealand laser profilometer include:

- the spot diameter is smaller (0.5 mm v 1 mm), providing improved resolution at short wavelengths;
- the vertical measurement range is larger (to a maximum of 32 mm v. 16 mm);
- the traverse length is greater (to a maximum of 1.7 m v. 1.0 m).

2.2 Research Tasks

Task 1: Linear Carriage Development

Design, fabricate and test a linear carriage which allows the laser camera to travel along a 1.5–2.0 m long beam at a steady speed of 20 to 100 mm/s. The carriage will be motor driven and its speed of travel fully controllable. The motor will have sufficient power to drive the 10 kg laser camera up a 15 ° slope.

Comment

The selected traverse speed is 145 mm/s. The equipment operates satisfactorily up a 15° slope, with only a small reduction in traverse speed of less than 1%. This has no effect on the accuracy of the measurements.

Task 2: Software Development - Data Acquisition
Develop software to monitor the speed of the laser camera movement, record the output from the laser camera at specific spatial frequency, and monitor the percentage of measurement dropouts (i.e. received light intensity is too low, resulting in an invalid laser signal).

Comment
The invalid data signal from the laser is not monitored. Instead, the analysis software estimates the percentage of possibly invalid data by checking for sequences of constant measured profile height.

The laser output is recorded at a constant temporal (not spatial) frequency. Some slight variation in the length interval occurs between measurements caused by small variations in the traverse speed. A warning is issued in the analysis if the traverse speed variation exceeds 1%.

Task 3: Software Development - Signal Processing
Develop software to process the recorded profile signals. Three routines are proposed:

1. *Orthodox surface texture profile as a function of longitudinal distance;*
2. *The average octave band power spectrum calculated over a wavelength range of 0.2 mm to 1000 mm;*
3. *Pseudo-sand circle texture depth calculated from the average area under a line which touches the peaks of the surface texture profile curve.*

Comment
Third octave band spectral levels were calculated for wavelengths in the range 0.63 mm to 500 mm.

Task 4: Software Development - Profiles from Friction Course Surfaces
Develop software to handle laser profile data from porous friction course surfaces whereby measurement dropouts in the pores are substituted by draped catenaries to obtain a more realistic estimate of texture depth.

Comment
This technique has not been adopted. The measurements obtained from highly porous surfaces are reasonably satisfactory, and do not require the application of the draped catenary method.

Task 5: Commissioning and Testing
Commission the laser camera and conduct stability tests as recommended by Dr Ulf Sandberg from VTI. This will involve:

1. *Fabrication of a calibration surface (a 1 m long triangle profile, machined from aluminium) to enable comparison of theoretical and measured RMS texture depth and profile spectrum values;*

2. *Determining probe stability when it measures the profile of a rather smooth surface which has sudden black and white contrasts;*

3. *Determining background noise floor in third octave bands.*

Comment
The machined triangular calibration profile which has been manufactured for these tests is 500 mm long.

The laser operates satisfactorily on a shiny surface with sudden black and white contrasts, and on the triangular calibration block when it is fitted with a white surface. The laser cannot operate on a sloping mirrored surface, and consequently may also be expected to experience some data dropout for wet road surfaces.

3. DESIGN AND OPERATION OF INSTRUMENT

The laser profilometer is designed to be light enough to be carried by a single operator, while providing continuous traverse measurement of up to 1.7 m length. Figure 3.1 shows the completed equipment in operation. It comprises the following locally developed components in addition to the Selcom laser camera itself. Specification details of the system components are given in Table 3.1.

Frame
The frame is welded stainless steel angle, with four point contact on the surface to be measured, provided through height adjustable feet. A digital level is mounted on the top of the frame so that the traverse can be run level or preset to a particular slope appropriate for the surface, thus providing a known datum for the profile. The level can also be detached and used to set the transverse slope of the frame feet equal at each end, thereby ensuring that the frame is not twisted and that the laser beam operates in a single plane as intended.

Laser Camera Carriage
The laser camera is screwed to the carriage of a precision linear slide which is in turn bolted to the upper rail of the frame. The carriage uses recirculating ball races that run in vee grooves machined in the top and bottom flanges of the slide channel section. The camera and carriage is moved by a robust toothed belt that passes around a motor driven pulley at one end of the frame and an idler pulley at the other. Tensioning of the belt is achieved by moving the idler pulley. To eliminate possible clearance movement of the carriage, a small side thrust is kept on the ball races by clamping the belt to the carriage on a surface slightly proud of the tangent line between the two pulleys.

Figure 3.1 Laser profilometer in operation.

Reference Start and End Plates

The laser beam is aligned to pass centrally between two lower rails of the frame that connect the feet at each end. These rails are located slightly above the surface to be measured. Start and end plates within the laser beam measurement range can be positioned underneath at set points along these rails, to provide reference readings for the start and end positions of the measurement traverse. For the standard positions (start and end plates at set points B and S), the traverse length is 1655 mm. The height measurement range of the laser camera is 32 mm, measured down from the upper surfaces of the start and end plates.

Drive

The drive to the toothed belt pulley is provided by direct coupling of a DC motor and reduction gearbox to the pulley shaft. The motor speed is set to achieve a traverse speed of 145 mm/s. A relatively high torque motor is employed to minimise the potential for speed changes caused by the varying friction (or stiction) loading of the drive train over extended periods of use. A 10 turn precision rotary potentiometer is coupled to the gearbox output shaft to give a continuously recordable position signal for location of the carriage during a measurement traverse.

Motor Controller and Selcom Optocator

The motor controller is remote from the profilometer frame and incorporates stop, start and reverse switches as well as connections from safety stop micro-switches mounted on each end of the frame. Electrical connection of the controller to the motor and micro-switches is through an umbilical cable. A second cable contains the data signal connections from the laser conditioning unit mounted on the top of the frame, and from the rotary potentiometer mounted on the gearbox output shaft. The surface profile height reading made by the laser camera is converted to an analogue output signal in an "optocator interface module" unit which is also remote from the frame. This signal together with the potentiometer position signal are simultaneously logged using a laptop computer data acquisition system. The motor controller and the optocator interface module are both installed in a single control box.

Power Supply
All the components comprising the laser profilometer are powered by a standard 12V car battery.

Table 3.1 Specifications of the system components of Transit New Zealand's stationary laser profilometer.

Item	Specification
Frame	Stainless steel angle (30 x 30 x 3mm)
Digital level	SmartLevel (Pro Series)
Traverse rail and slide	Slidepack (THK FBW50110H + 18800L)
Drive belt and pulleys	PowerGrip HTD (26 tooth, width 20, pitch 8)
Motor	12V DC 50 rpm (RS No. 718-565)
Motor speed controller	12V DC (RS No. 440-486)
Linear potentiometer	Sakae Precision Class (20HHP-10S)
Laser camera and conditioning unit	Selcom (808097-2207-32/180-A)
Laser spot diameter	0.5 mm
Laser measurement range	32 mm (165 to 197 mm from lower surface of camera)
Optocator interface module	Selcom (805870 and 804212)
Data collection/processing	Laptop PC equipped with Advantech DACpad-71A data acquisition unit, LabTech Notebook for Windows data acquisition software, and MATLAB for Windows data analysis software
Data sampling rate	500 samples per second per channel

On-road Operation

Operation of the laser profilometer can be performed by one skilled operator and is reasonably straightforward. In addition, traffic control procedures are required.

The laser profilometer is transported to the measurement site by van. The van is parked facing oncoming traffic in the lane to be measured, and all measurements are taken from the back of the van where the sampling and control units are set up.

At each location the laser profilometer is placed on the ground, and the height from the laser to the pavement is adjusted to provide the maximum valid measurement range for the surface. A preliminary scan is performed to ensure valid readings are obtained and all system components are operating satisfactorily. A single traverse of the site is made, with both the height and distance recorded through the sampling routine. The road section slope, traverse time, and supply battery voltage are also manually recorded. The data are displayed on the computer screen and visually checked for validity. The laser profilometer is then moved to the next location.

A survey of a 200-m long site (11 locations at 20-m intervals) can be completed within two hours, including data analysis.

4. ASSESSMENT OF AS-BUILT INSTRUMENT PERFORMANCE

4.1 Laser Equipment

The laser equipment has been found to operate satisfactorily within the limitations of the accuracy of the height measurements as described in Section 6 of this report.

The equipment produces a visual indication, by means of an indicator light, that invalid data have been recorded (e.g. if the surface height is outside the range of the laser, or if insufficient reflected laser light has been detected) but this information is not itself recorded. An invalid measurement is replaced by the last valid measurement obtained. In order to identify possible invalid data, the analysis program checks if the measured voltage remains constant over several consecutive samples. If voltage is constant, it is an indication that the data may be invalid (or that the surface is very smooth).

Task 4 was to develop a method to replace invalid data with theoretical draped catenary curves, in order to obtain realistic estimates of texture depth for friction course surfaces. As the invalid data indication is not recorded, this has not been possible. However, in the examples recorded in Appendix 2, a reasonably satisfactory surface measurement can be obtained even when some of the data are invalid.

Therefore the influence of invalid data on the accuracy of the measured texture depth appears acceptable, even in the case of porous friction course surfaces.

4.2 Traverse Mechanism

Despite the considerable care applied to the design of the traverse mechanism, some difficulties have been experienced with its operation. This has included failure of the first drive motor that was installed.

The traverser is set to operate at a constant speed of 145 mm/s. Although operating the traverser at slower speeds would be desirable, this is not recommended with the drive motor/gearbox combination as installed, because this would place undesirable loading on the drive motor. Also the speed of the traverser is not exactly constant, with the speed varying within a single test, as well as from test to test.

Within a single test the typical speed variation is less than 1% (i.e. ±1.5 mm/s) as the traverser moves along the track after the initial acceleration period. A greater degree of variation has been experienced for different tests, with the average speed ranging between 140 mm/s to 150 mm/s on some occasions. This is undesirable because data collection operates at a constant frequency of 500 Hz, and therefore the spatial interval between measurements (about 0.29 mm) is not constant.

For accurate measurement of a road surface profile, height measurements would be better obtained at precise horizontal distances (spatial intervals). This could be achieved by triggering sampling by pulses generated from a precision rotary encoder fitted to the drive shaft. Another alternative would be to numerically re-sample the original data at fixed spatial intervals using the potentiometer measurement as the reference.

At present the length measurement from the potentiometer is used only to plot the representative section of the measured profile, and to check the traverse speed linearity. This length measurement is not used in any of the wavelength analysis. The wavelength analysis therefore assumes that the traverse speed is constant, and this assumption is satisfactory as long as the measured traverse speed variation is less than 1%. Also, with this degree of traverse speed variation, the corresponding error introduced in the texture measurements is negligible under normal operating conditions. If the traverse mechanism should be interrupted or should vary significantly in speed for any reason, then a warning is printed on the analysis output and the test should be repeated.

The length measurement (in mm) is less accurate than the height measurement because the length range is much greater than the height range. The 12 bit, 0-10 volts A-D (analogue to digital) unit gives an output of 1 bit equivalent to 0.5 mm travel. Allowing for an A-D error of ±1 bit therefore gives an accuracy of about ±1 mm for any single length measurement.

Low pass filtering at 5Hz of the whole of the recorded length signal eliminates much of the A-D error, and increases the apparent precision of the length measurement to about ±0.02 mm. (This filtering also helps to eliminate the small amount of cross-talk from the laser signal which is measured by the A-D unit.) In addition, there is the influence of non-linearity of the potentiometer which has a specification of ±0.1%, i.e. error caused by non-linearity is less than ±2 mm over the full length of the laser profilometer.

5. CALIBRATION PROCEDURE

Calibration of the laser profilometer consists of a primary calibration plus an on-site check.

Primary Calibration
The primary calibration is achieved using a series of precision calibration blocks of different heights. The laser and recording equipment has been found to be linear over its range, and the current calibration (as at 12 November 1996) has been incorporated into the analysis program:

1 volt = 3.2709 mm

This calibration should be checked annually, or more frequently if indicated by the on-site check.

On-site Calibration
The method of on-site calibration involves the use of a 500 mm-long test section consisting of a machined triangular profile of nominally 10 mm height and 20 mm wavelength. ISO 13473-1 requires that this test section is measured and analysed at the beginning and end of each measuring day.

The on-site calibration should check that:

- the measured profile appears realistic, with no apparent defects; and
- the measured third octave band spectral level is 69.1 dB for 20 mm wavelength.

6. ACCURACY OF LASER HEIGHT MEASUREMENTS

The main influences on the accuracy of the laser height measurements are:

- Laser spot size
- Sag and ripple of profilometer beam
- Vibration caused by traverse mechanism
- Electronic noise

1. *Laser Spot Size*

The laser spot size is nominally 0.5 mm in diameter. Therefore, essentially no information can be measured for wavelengths less than 0.5 mm. As well, the measured amplitude is reduced at wavelengths above 0.5 mm. It can be theoretically demonstrated (assuming a square spot shape for simplicity) that the measured amplitude for a perfect triangular surface profile varies, as follows, with triangle wavelength:

Wavelength (mm)	Measured Amplitude (Ratio of True Amplitude)
0.5	0
1	0.5
2	0.75
4	0.875
8	0.938
etc.	...

For example, for the triangular calibration section with wavelength of 20 mm and amplitude of 10 mm, the theoretical measured amplitude related to the influence of the spot size is 9.73 mm. In practice, the measured amplitude for the machined triangular calibration profile is 9.72 mm. For the low pass filtered data used to calculate MPD, this reduces to 9.43 mm.

2. *Sag and Ripple of Profilometer Beam*

The sag of the beam has been measured to be 0.17 mm at the centre of the beam for the standard test section length (1657 mm). However, this can be expected to vary over time as the equipment is used.

For shorter test lengths the effects of sag are much less, e.g. for 100 mm test length the maximum sag is about 0.003 mm. Consequently the sag has negligible effect on road surface texture measurements.

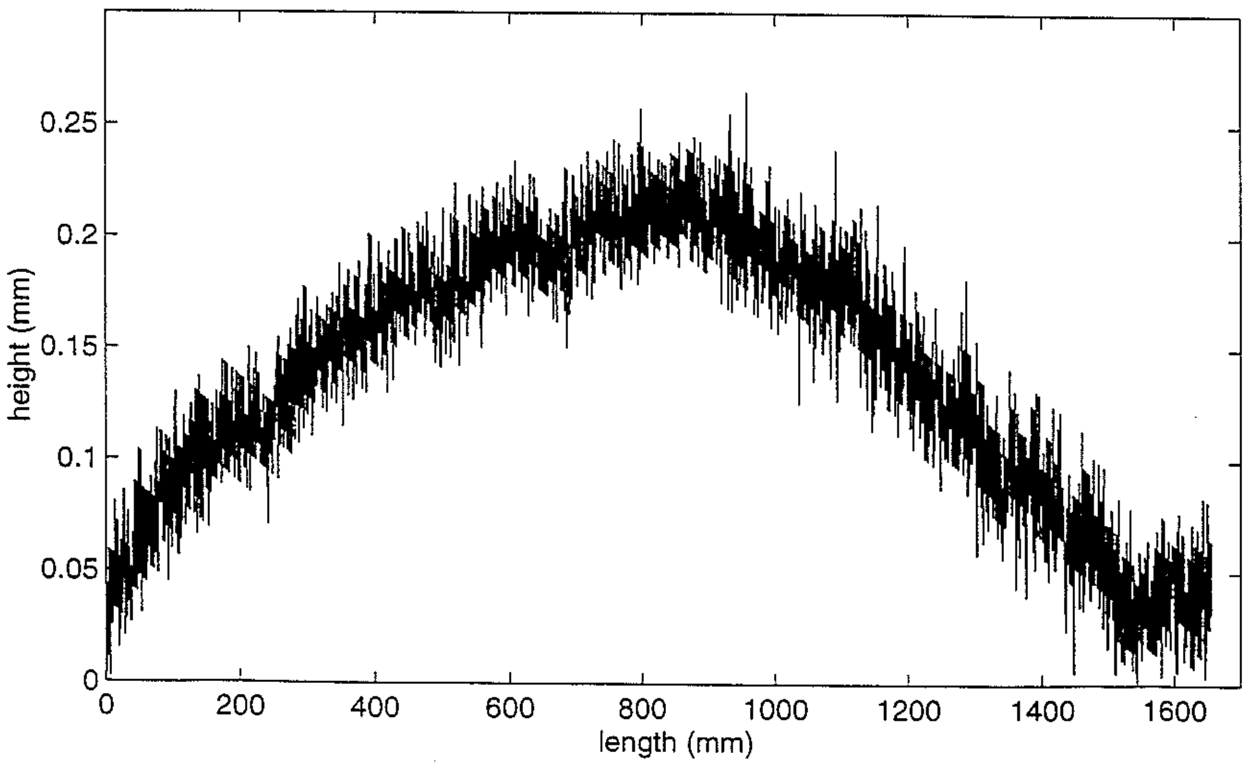
Typical profilometer measurements also show some ripple (or waviness) with amplitude of around 0.015 mm and wavelength of around 100 mm. This is also most likely to be caused by non-linearity of the profilometer beam.

3. *Vibration caused by Traverse Mechanism*
Some random signal noise is caused by the motion of the laser. This causes a measurement error of about ±0.03 mm on a flat surface. The error increases somewhat for a sloping surface, e.g. for a 45° slope (as on the triangular calibration section) the error is about ±0.05 mm. The wavelength of the measurement noise is typically about 1 mm. Low pass filtering at 2.5 mm wavelengths, as used in the calculation of MPD, reduces the noise by about half.

4. *Electronic Noise*
The error caused by high frequency electronic noise is about ±0.02 mm. This source of error would almost largely be eliminated by collecting a larger number of measurements (e.g. by increasing sampling rate from 500 Hz to say 2500 Hz), and then digitally filtering the data. However, as this source of error is substantially smaller than the error caused by the motion of the laser, the benefit of removing this electronic noise would be small.

5. *Combined Effects*
The combined effects of items 2, 3 and 4 are demonstrated in Figure 6.1, which shows the variation in measured height for a flat, polished bench surface.

Figure 6.1 Height measurements for a polished bench surface.



7. DATA ANALYSIS

The laser profilometer output data is analysed using the MATLAB program *ROADPRO2* (developed from an earlier program *ROADPRO*). The program produces three pages of output. The first two pages of output are as shown in Figure 7.1a and b (the third page of output is essentially a visual data check for the operator). A typical printout for a grade 2 chipseal surface is shown. Additional examples for seven different road surface types are presented in Appendix 2.

7.1 Inputs

Required inputs:

1. Data filename. The data consist of two columns of voltages, sampled at 500 Hz. These are the laser and potentiometer measurements. The end plates are automatically detected by the program, and the data between them are analysed. If the program does not detect two end plates, then all the data are analysed.
2. Test section length (mm).

Optional inputs:

1. Test date.
2. Site identification.
3. Wheelpath.
4. Site description.
5. Comments.
6. Operator.

The analysis can be run by entering all the inputs as they are requested by the program. Alternatively, a *.pcf* text file can be used which includes all the inputs for analysis of multiple data files.

MATLAB is a technical computing environment for high performance numeric computation and visualisation. It is produced by 'The MathWorks'.

7.2 Analysis

The following information is presented in the *ROADPRO2* output, an example of which is shown in Figures 7.1a and b (**1-11** are explained in the following notes **1-11**)

Page 1 (Figure 7.1a)

1. The test section length in mm and average traverse speed in mm/s, assuming 500 samples per second per channel sampling rate.

2. Traverse speed variation (%). The traverse speed variation is calculated by fitting a best fit straight line to the potentiometer measurements and calculating the maximum deviation from this line. Although the traverse speed is not perfectly constant, the variation should be less than 1%.

A "WARNING >1%" message is printed if the speed variation is greater than 1%.

3. Maximum and minimum voltages. These should be between 0 and 10 volts, in which case an "OK" message is printed. Otherwise a "WARNING OUT OF RANGE" message is printed.

4. Possible invalid data (%). If the laser is unable to obtain a valid measurement (e.g. if there is a hole in the road surface) then it transmits the last valid measurement until a new valid measurement is obtained. This is a potentially misleading situation. Therefore the program searches for sequences of constant voltage and identifies them as possible invalid data. This therefore means that some valid data are also likely to be identified as possible invalid data.

A "WARNING >10%" message is printed if the possible invalid data are greater than 10% of the total data. This warning appears more commonly for very smooth surfaces than for rough surfaces, as the computer analysis is unable to distinguish between a very smooth surface and an invalid data point. The measured possible invalid data are typically about 1-2% for a road surface, and therefore the warning does not appear.

5. Mean, standard deviation, maximum and minimum measured heights, in mm. These values should lie within the measurement range of the laser (0-32 mm).

6. A full scale plot of the first 160 mm of the measured data.

7. Pavement texture measurements. These are calculated using the third octave band spectral levels presented on page 2 of the output. The various measures of pavement texture are as described by Sandberg and Anund (1993). The use of dB for these measurements is preferred by Sandberg (1989), but they can also be expressed as mm RMS, and so these values are also provided in brackets.

Figure 7.1a *ROADPRO2* output, page 1.

See Section 7.2 of this report for explanations of **1 - 8**, p. 6 for Abbreviations

LASER PROFILOMETER
ROAD PROFILE MEASUREMENT AND ANALYSIS

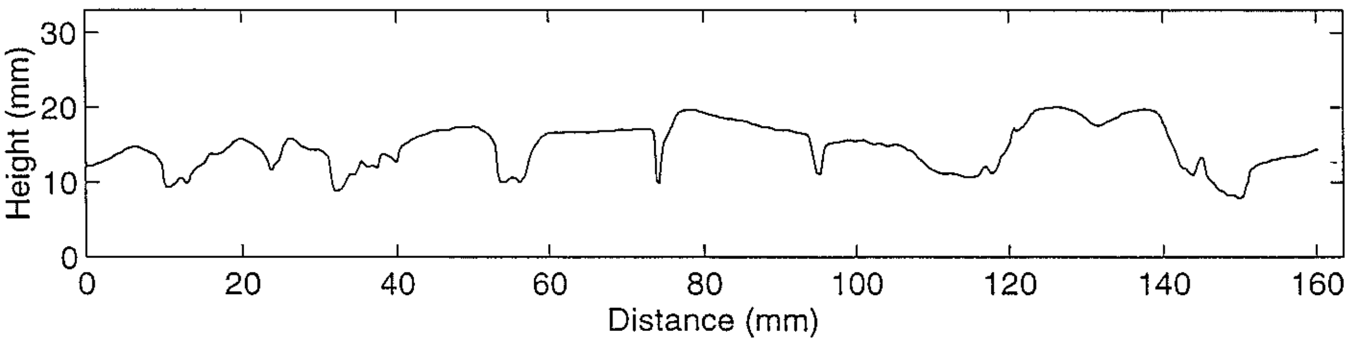
Data File: txtur1a.dat p1/2
Analysed 3-Dec-96 15:1

WORKS CONSULTANCY SERVICES LTD, CENTRAL LABORATORIES, roadpro.m version 3-December-1996

Test Date : 4 Oct 96
Site Identification : SH1 south of Plimmerton
Wheelpath :
Site Description : Grade 2 Chipseal
Comments : 2nd of 10 locations
Operator : Doug Brown

1. Test section length : 1657 mm Traverse speed : 145.9 mm/s
2. Traverse speed variation (%) : 0.8077 ok <1%
Sampled 5679 points @ 500 Hz
3. Maximum voltage : 6.511 Minimum voltage : 2.087 ok
4. Possible invalid data (%) : 3.17
Effect of overall slope has been removed from all height analysis.
5. Mean height : 15.98 mm Std dev height: 2.798 mm
Maximum height : 20.93 mm Minimum height: 7.117 mm

6. Section of measured profile - first 160mm



7. Pavement texture measurements

Lma : 65.95 dB(Ma) (1.984 mm rms)
Lme : 62 dB(Me) (1.258 mm rms)
L5mm : 55.54 dB(5mm) (0.5982 mm rms)
L80mm : 59.49 dB(80mm) (0.9425 mm rms)
Tdma : 4.363 mm
ERNL : 75.86 dB(A)

8. Mean Profile Depth analysis to ISO Standard 13473-1

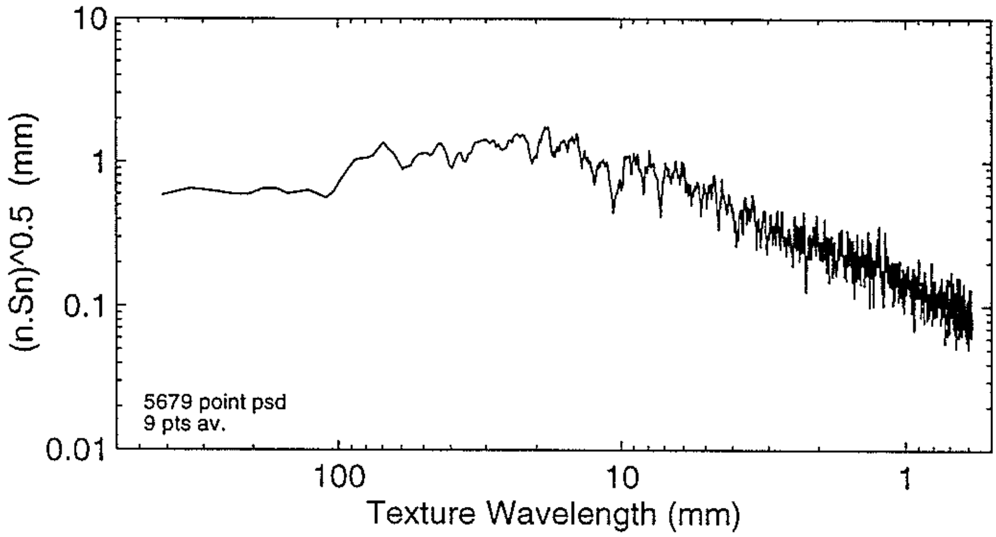
The following measurements based on the average of 16 segments of 100 mm.
MPD : 3.435 mm ETD : 2.948 mm RMS : 2.366 mm
Standard deviation of individual MPD values : 0.9302 mm

Figure 7.1b *ROADPRO2* output, page 2.

See Section 7.2 of this report for explanations of **9 - 11**, p. 6 for Abbreviations

9.

Data File: txturl a.dat p2/2
Analysed 3-Dec-96 15:1



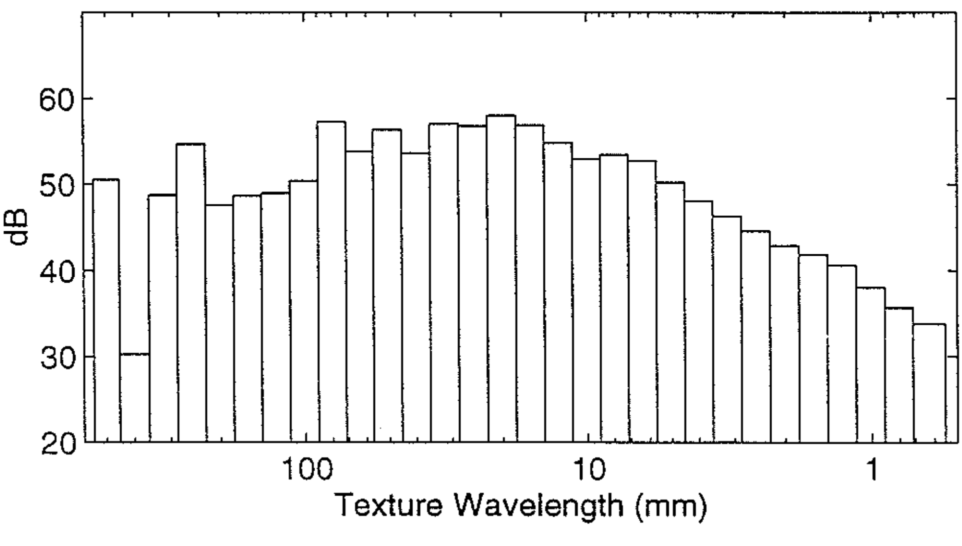
10.

Third-Octave Band Spectral Levels

Wavelengths and texture levels (dB relative to 0.001 mm std)

500 mm	50.6 dB	50 mm	56.4 dB	5 mm	50.2 dB
400 mm	30.3 dB	40 mm	53.6 dB	4 mm	48.1 dB
315 mm	48.8 dB	31.5mm	57 dB	3.15mm	46.3 dB
250 mm	54.7 dB	25 mm	56.8 dB	2.5 mm	44.6 dB
200 mm	47.6 dB	20 mm	58 dB	2 mm	42.9 dB
160 mm	48.7 dB	16 mm	56.9 dB	1.6 mm	41.8 dB
125 mm	49 dB	12.5mm	54.8 dB	1.25mm	40.6 dB
100 mm	50.4 dB	10 mm	53 dB	1 mm	38 dB
80 mm	57.3 dB	8 mm	53.4 dB	0.8 mm	35.7 dB
63 mm	53.8 dB	6.3 mm	52.8 dB	0.63mm	33.8 dB

11.



The conversion from dB to mm RMS is:

$$\text{mm RMS} = 0.001 * 10^{(dB/20)}$$

Lma : The so-called "Macrotexture Level". This is the combined dB measurement within the 2 mm to 50 mm third octave band ranges.

Lme : The so-called "Megatexture Level". This is the combined dB measurement within the 63 mm to 500 mm third octave band ranges.

L5mm : The combined dB measurement for the 5 mm octave band (i.e. the 4, 5 and 6.3 mm third octave bands combined). This is known to be a good predictor of tyre/road noise characteristics in the high frequency range (1000 Hz and above).

L80mm : The combined dB measurement for the 80 mm octave band (i.e. the 63, 80 and 100 mm third octave bands combined). This is known to be a good predictor of tyre/road noise characteristics in the low frequency range (below 1000 Hz).

Tdma : The texture depth in mm predicted from the macrotexture level, Lma. The texture depth predicted is the same as ETD tries to predict, i.e. the texture depth obtained from volumetric measurements (the "sand patch" method).

The empirically obtained relationship is:

$$\text{Tdma} = (0.0023 * 10^{\text{Lma}/20}) - 0.2 \quad \text{(mm)}$$

ERNL : This is the estimated road noise level in dB predicted from the L5mm and L80mm measurements. The empirically obtained relationship is:

$$\text{ERNL} = \frac{\text{L80mm}}{2} - \frac{\text{L5mm}}{4} + 60 \quad \text{(dB)}$$

8. Mean profile depth analysis. These values are calculated using the procedure described in ISO 13473-1 (1996).

MPD : Mean profile depth, in mm. This is the average value of a series of individual MPD values calculated for 100 mm-long profile segments (or baseline lengths).

For each segment the measured profile is low-pass filtered at 2.5 mm wavelength, the mean slope of the segment is suppressed, and the average depth of the segment profile is then calculated using the average of the highest peak in each of two 50 mm sub-segments as the reference height.

ETD : Estimated texture depth, in mm.

ETD = 0.2 + 0.8 MPD

This transformation equation is used to calculate ETD values which are as close as possible to texture depth measurements using the volumetric patch method (MTD).

ISO 13473-1 states that use of MPD is preferred to ETD as a measure of texture depth.

Note that these calculations for MPD and ETD are different to those used in the International PIARC Experiment. This difference is discussed in Appendix E of the PIARC (1995) report.

RMS : The average standard deviation (in mm) of the profile segments used for the MPD calculation (after low pass filtering and slope suppression).

Standard Deviation of Individual MPD Values:
A measure of the variation between MPD values for each 100 mm profile segment.

Page 2 (Figure 7.1b)

9. A conventional psd (power spectral density) analysis for the measured profile, plotted as texture wavelength in mm v. $(n \,.\, Sn)^{1/2}$ in mm. This information is used to derive the third octave band analysis presented below. The length of the psd is the smaller of:

(a) 8192,

(b) the number of sample points.

A nine point moving average is applied to the plotted spectrum.

10. Third octave band spectral levels, in dB, for the wavelength range 500 mm to 0.63 mm inclusive. The dB values are calculated relative to a standard deviation of 0.001 mm in each band, i.e. 60 dB is equivalent to 1 mm standard deviation within the band.

Note that measurements at both the high and low ends of this spectrum need to be treated with some caution.

(a) For a typical profile of about 1600 mm length, the 500 mm third octave band measurement is derived from only three 500 mm profile segments, and therefore may not be representative of a greater length of consistent road surface. The measurements for wavelengths of 200 mm and below are derived from enough measurements that they are likely to be representative of a greater length of consistent road surface.

(b) For small wavelengths, as discussed in Section 6 of this report, the effects of laser spot size averaging and measurement error become significant for wavelengths less than about 2.5 mm.

The calculation of MPD is based on analysis of data in the range 2.5 mm to 100 mm wavelengths, and this is also a reasonable indicator of the most reliable range of the third octave band analysis.

11. A plot of the third octave band spectral levels listed above. This plot essentially presents the same information as in the spectrum at the top of the page, but in a simplified form.

8. REPEATABILITY OF MEASUREMENTS

A series of measurements of a representative grade 4 chipseal road surface was performed to test the repeatability of nominally identical measurements. Ten 1657 m-long sections of road were each measured twice by the laser profilometer. The laser profilometer was not moved between the first and the second measurement in each case.

Some variation occurred between the measurements in each pair. This is believed to be mainly related to the variation in the longitudinal location of each height measurement, because the measurements are taken at approximately 0.3 mm intervals. Some contribution to this variation is also related to the mechanical vibration and electronic noise effects. In addition, the extent to which any variation of the lateral position of the laser spot may influence the repeatability of the measurements is unknown.

The variation between MPD measurements for the road has been analysed and the following results were obtained.

- The overall average of the 20 MPD measurements was 2.38 mm.
- The average difference between the two MPD measurements in each pair was 0.9% (0.022 mm).
- The highest difference between the two MPD measurements in each pair was 2.4% (0.064 mm).
- The difference between the largest and smallest MPD measurements from all 20 runs was 34% (0.71 mm). The RMS variation was 0.24 mm.

Consequently the difference between nominally identical measurements may be quite significant, but the variation between different sections of the same road is substantially more significant.

9. RECOMMENDATIONS FOR FURTHER DEVELOPMENTS

9.1 Measurement of Golden Speed Constant (Sp)

One outcome of the International PIARC Experiment (PIARC 1995) was the proposed use of an International Friction Index (IFI). The friction characteristics of a road surface are described by two separate measurements: the so-called golden speed constant (Sp), and the golden friction at 60 km/h (F60). These two measurements are reported as the International Friction Index, IFI (F60, Sp).

The aim of the use of IFI is to enable measurements obtained with a wide range of different equipment to be expressed in a consistent manner. The laser profilometer measures surface texture, which is characterised by the golden speed constant, Sp.

Recommendation
The laser profilometer should be further developed to provide a measurement of Sp. The calculated Sp should be calibrated against Sp measurements obtained using equipment which was used in the International PIARC Experiment. These include the volumetric patch (or sand circle) method and the outflow meter method.

9.2 Distance Measurements

Recommendation
An accurate horizontal distance measurement should be incorporated into the analysis, so that the traverse speed no longer needs to be precisely constant. The recording equipment would then be configured to obtain height measurements at fixed distance intervals.

However, a simpler alternative would be to numerically re-sample the data so that it has the appearance of having been measured at fixed distance intervals. This would negate possible anomalies caused by variations in the horizontal speed of the laser, and could be achieved without any major hardware changes.

9.3 Height Measurements

Recommendation
The accuracy of profile measurements could be significantly improved by performing height measurements at the reduced interval of less than 0.1 mm, instead of the interval of 0.3 mm used at present. This reduced spatial sampling interval can be achieved by either increasing the sampling rate or reducing the traverse speed.

9.4 Laser Equipment

Since the Selcom laser camera for the Transit New Zealand laser profilometer was purchased, a number of improvements have been incorporated in the latest Selcom laser design. These improvements include:

- Smaller diameter laser spot: this provides improved resolution at small wavelengths.
- More compact design: the complete unit has been reduced in size from three separate boxes to a single compact box.
- Automatic laser power modification: power output is automatically increased if the reflected signal is low (e.g. on a wet surface). This allows the laser to operate at increased power for short periods without reducing the expected operating life.

Recommendation:
Recent improvements to laser camera technology have been incremental rather than major ones. So quantification of road microtexture, i.e. road profile wavelengths less than 0.1 mm, which is known to directly affect skid resistance and tyre wear, is still not possible. Accordingly, the existing laser equipment should not be replaced with new generation 64 kHz lasers at this point in time.

10. REFERENCES

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Sandberg, U. 1989. Measurement of road surface texture and tyre/road friction. *Road Research Unit Occasional Paper,* National Roads Board, New Zealand.

Sandberg, U., Anund, P. 1993. Measurements of macrotexture by the VTI mobile laser profilometer in the PIARC International Experiment 1992. *VTI Notat TF 52-20,* Väg-och Trafik-Institutet, Sweden.

APPENDIX 1
LISTING OF MATLAB PROGRAM *ROADPRO2*

LISTING OF MATLAB PROGRAM *ROADPRO2*

```
clc
clear
echo on

program='roadpro2.m    version 17-April-1997';

% Project file: 529340.00
% Computer directory: H:\MATCLABS

% Paul Carpenter

% MATLAB program to analyse data from laser profilometer and produce
% 3-page output of pavement texture statistics.

%     roadpro2.m is a modified version of roadpro.m
% 1. EITHER single data files can be analysed
%     OR multiple data files are specified from a .pcf program control file.
% 2. EITHER no laser profilometer end plates are detected, and all the data is analysed
%     OR end plates are detected, and only the data between the end plates is analysed.

% Non-standard functions called.
%     bar_m1.m      Same as bar.m, but calculates histogram without gaps between the bars.
%     datetime      Calculates the date and time.

% Assumptions
% 1. Data is two columns of ASCII data, measured in volts, sampled at 500Hz, without
%     header lines.
% 2. Column 1 consists of road surface measurements, plus optional end plates at a
%     height giving output of greater than 9.7 Volts.
% 3. Column 2 consists of potentiometer measurements.
% 4. Traversing mechanism of laser profilometer should operate at constant speed
%     over the measured profile. The linearity is checked from the potentiometer data.
% 5. Length of measured profile is known, measured between endplates.
% 6. The optional .pcf program control file contains, for each data file to be analysed,
%     eight lines corresponding to the eight manual input lines,followed by y or n to
%     indicate subsequent data, for each of the data files to be analysed.

echo off


% Outputs
% 1.   3-page .ps print file
%       Page 1: road profile measurements (MPD etc)
%       Page 2: third-octave band analysis
%       Page 3: original data
% 2.   .ob ASCII file - third-octave band analysis data
% 3.   .mpd ASCII file - individual 100mm MPD values


% Measured calibration of laser profilometer.
% Change here if new calibration is measured.

calibration=3.2709;      % 1 volt = 3.2709 mm (Doug Brown, 12 Nov 1996).
fsamp=500;               % Sampling rate = 500Hz.


inputfile=input('Enter full name of the data file or .pcf file :  ','s');
n=length(inputfile);
anothertest='y';     % Initial setting.

if inputfile((n-2):n)~='pcf'    % If not using a program control file.
    pcf='n';
    infname=inputfile;
    i=1;                          % find position of "." in the filename.
    while ((infname(i+1)~='.') & (i~=n))
       i=i+1;
    end
    infile=infname(1:i);          % infile is infname without the extension.
    endsep=input('Enter endplate separation (profile length if no endplates) (mm) : ');
    testdate=input('Enter test date (optional) : ','s');
    siteid=input('Enter site identification (optional -60 chars max) : ','s');
    wheelpath=input('Enter wheelpath identification (optional -60 chars max) : ','s');
    description=input('Enter site description (optional -60 chars max) : ','s');
    comments=input('Enter comments (optional -60 chars max) : ','s');
    operator=input('Enter operator name (optional) : ','s');

    % Go to MAIN LOOP

else     % Using program control file, read inputs for first data file.

    pcf='y';
    readpcf=fopen(inputfile,'r');     % open program control file to read inputs.
    infname=fscanf(readpcf,'%s',1);
    nn=length(infname);
    i=1;                          % find position of "." in the filename.
    while ((infname(i+1)~='.') & (i~=nn))
       i=i+1;
    end
```

```
    infile=infname(1:i);           % infile is infname without the extension.
    endsep=fscanf(readpcf,'%f/n');
    testdate=fgetl(readpcf);
    siteid=fgetl(readpcf);
    wheelpath=fgetl(readpcf);
    description=fgetl(readpcf);
    comments=fgetl(readpcf);
    operator=fgetl(readpcf);
end


while anothertest=='y'

%***************** MAIN LOOP ************************************************************


% Load data.

disp ' '
disp 'Loading data file '
eval(['disp ',infname])
load (infname)               % Loads data into variable named contents of infile.
datv= eval([infile]);        % Copies data into variable named datv.
eval(['clear ',infile])      % Clears the first copy of the data.
[nsamples,n]=size(datv);
disp(['File size is ',num2str(nsamples,10),' by ',num2str(n,10)])
disp ' '


% Search for data between two endplates.
% Each endplate must be at least 50 samples long, and always greater than 9.7 volts.
% If no such endplates are found, then all the data is analysed.

index=find(datv(:,1)>9.7);
lenind=length(index);

if lenind<100    % i.e. 2 endplates must be at least 100 samples long.
    disp 'Endplates not found. Analysing all data.'
    testlength=endsep;
    laserv=datv(:,1);
    potv=datv(:,2);
    % Go to FILTER

else
    disp 'Endplates found.'

    % Firstly find first point after first endplate.
    firstpoint=0;
    for i=51:lenind
        if (index(i)-index(i-50))>49 & (index(i)-index(i-1))>1 & firstpoint<1
            firstpoint=index(i-1)+1;
        end
    end

    % Then find last point before second endplate.
    lastpoint=0;
    index=flipud(index);     % Work backwards.
    for i=51:lenind
        if (index(i-50)-index(i))>49 & (index(i-1)-index(i))>1 & lastpoint<1
            lastpoint=index(i-1)-1;
        end
    end

    firstdata=firstpoint+3;    % Don't use the first 3 points after the endplate.
    lastdata=lastpoint-3;
    nsamples=lastdata-firstdata+1;
    testlength=endsep-(5.66*endsep/nsamples); % ie typically reduces length by 1.7mm due
                                              % to omitting 3 data points from each end.
    laserv=datv(firstdata:lastdata,1);
    potv=datv(firstdata:lastdata,2);
end

% FILTER
% Low-pass filter potentiometer for calculation of traverse distance.
% Note that the very low frequency is required to eliminate most of the cross talk
% between the laser and potentiometer (i.e. some of the laser signal is picked up
% in the potentiometer measurements).

[b2,a2]=butter(4,5/(fsamp/2));        % 4th order Butterworth low-pass filter at 5 Hz.
potvrange=potv(nsamples)-potv(1);     % These few line triple the length of the
tmp1=potv-potvrange;                  % potentiometer data so that it can be low-pass
tmp2=potv+potvrange;                  % filtered at a low frequency without distortion.
potvfilttmp=filtfilt(b2,a2,[tmp1;potv;tmp2]);      % Zero-phase filtering.
potvfilt=potvfilttmp(nsamples+1:(2*nsamples));
clear potvfilttmp
clear tmp1
clear tmp2
clear potv
```

```
% Calculate average traverse speed (mm/s), and check linearity of traverse speed.

vel=testlength*fsamp/nsamples;
potvdet=detrend(potvfilt);
potstart=potvfilt(1);           % Initial pot voltage.
potend=potvfilt(nsamples);      % Final pot voltage.
potnonlin=100*max(potvdet)/abs(potend-potstart);
clear potvdet

% Calculate distance column

distmm=testlength*(potvfilt-potstart)/(potend-potstart);
clear potvfilt


% Check voltage range

vmax=max(laserv);
vmin=min(laserv);


% Count (roughly) possible invalid data points by checking if 5 consecutive points
% are all within 3 bits of each other (which typically happens less than a few
% percent of the time except on a very smooth surface or a very rough surface).

i=1;
dropcount=0;
while i<nsamples-4
    if abs(laserv(i+1)-laserv(i))<0.008...      % Look for 5 similar consecutive points.
    & abs(laserv(i+2)-laserv(i))<0.008...
    & abs(laserv(i+3)-laserv(i))<0.008...
    & abs(laserv(i+4)-laserv(i))<0.008
        dropcount=dropcount+5;
        i=i+5;
        while i<nsamples & abs(laserv(i)-laserv(i-1))<0.008  % Look for additional
            dropcount=dropcount+1;                           % similar point.
            i=i+1;
        end
    else i=i+1;
    end
end
droppercent=100*dropcount/nsamples;


% For road profile analysis, data is converted to mm, and is detrended so that any
% effect of the overall slope of the surface is removed.

datamm=laserv.*calibration;     % Convert volts to mm.
clear laserv
datamm=detrend(datamm)+mean(datamm);     % Remove average slope from data.
datamean=mean(datamm);
datastd=std(datamm);
datamax=max(datamm);
datamin=min(datamm);


% Define wavelength ranges to analyse.

lambdacentre=20;      % Middle of wavelength octave band range (mm).
obs=log10(vel/lambdacentre)-1.4;      % Gives 14 bands left of centre band.
obf=log10(vel/lambdacentre)+1.5;      % Gives 15 bands right of centre band.


% Calculate dB's relative to 0dB = 0.001mm std in each band.
% ie 60dB = 1mm std.

zerodbstd=0.001;


% Calculate psd, maximizing size if available data length is small.

if nsamples<8192
    nfft=nsamples;
else
    nfft=8192;
end
[p1,f]=psd(datamm,nfft,fsamp,'linear');     % Returns columnns (nfft/2 long) of
                                            % p1 and frequency in Hz.
psdstd=sqrt(mean(p1));                      % Standard deviation calculated from psd.
sn=p1/(fsamp/2);         % Divide by Nyquist frequency (half sampling frequency)
                         % to calculate sn in mm^2/Hz.


% Check that psd has been correctly calculated using Parseval's Theorem.

avgdbdata=20*log10(datastd/zerodbstd);
avgdbpsd=20*log10(psdstd/zerodbstd);
% disp(['Detrended std                    = ',num2str(datastd)])
```

```
% disp(['Should be equal to std from psd = ',num2str(psdstd)])
% disp(['Average dB from standard std    = ',num2str(avgdbdata)])
% disp(['Average dB from psd std is      = ',num2str(avgdbpsd)])


% Convert spectrum to mm.

nsnsqrt=sqrt(sn.*f);
clear sn


% Apply 'nav' point moving average.

[m1,n1]=size(nsnsqrt);
nav=9;  % nav must be an odd number.
nin=(nav-1)/2;
np=m1-nav+1;
p3=zeros(np,1);   % p3 is 'nav' point moving average of nsnsqrt.
f3=zeros(np,1);   % f3 is frequency of p3.
j=1;
for i=1+nin:np+nin;
       f3(j)=f(i);
       p3(j)=(sum(nsnsqrt(i-nin:i+nin))/nav);
       j=j+1;
end


% Do third-octave band analysis over wavelength band range
% specified by obs & obf.

na=10^(obs-0.05);     % Frequency in Hz of lowest frequency included in analysis.
nb=10^(obf+0.05);     % Frequency in Hz of highest frequency included in analysis.

i=1;                  % Starting value for i.
n=obs;                % Starting value for n.
while n<=obf+0.1
     n1=10^(n-0.05);                % Minimum frequency of third-octave band.
     n2=10^(n+0.05);                % Maximum frequency of third-octave band.
     ind1=find(f>=n1 & f<n2);       % Returns the indices of f within the range n1<=f<n2.
     oct3std=sqrt(sum(p1(ind1))/sum(p1))*psdstd;    % Rms of third-octave band.
     if  oct3std==0
         db=0;        % Prevents log10 of zero error.
     else
         db=20*log10(oct3std/zerodbstd);    % Convert rms to dB.
     end

% Create matrix ob to be saved in ASCII output file.
     obrow(i,1)=i;
     obfreq(i,1)=10^n;
     oboct3std(i,1)=oct3std;
     obdb(i,1)=db;

     n=n+0.1;
     i=i+1;
end

lambda=vel./obfreq;     % Calculate wavelengths in mm.
f3lambda=vel./f3;

ob=[obrow,obfreq,lambda,oboct3std,obdb];
eval(['save ',infile,'.ob ob -ascii']);     % Save ob values to 'infile'.ob file.


% Calculate Lma, Lme, L5mm, L80mm, Tdma, and ERNL as defined in VTI TF52-20  p19-24.

ind=find(lambda>19.99 & lambda<20.01);                         % Find position of 20mm band.
lma = 20*log10(sqrt(sum(oboct3std(ind-4:ind+10).^2))/zerodbstd);  % 2mm to 50mm bands.
lme = 20*log10(sqrt(sum(oboct3std(ind-14:ind-5).^2))/zerodbstd);  % 63mm to 500mm bands.
l5mm =20*log10(sqrt(sum(oboct3std(ind+5 :ind+7).^2))/zerodbstd);  % 4mm to 6.3mm bands.
l80mm=20*log10(sqrt(sum(oboct3std(ind-7 :ind-5).^2))/zerodbstd);  % 63mm to 100mm bands.
tdma=0.0023*10.^(lma/20) -0.2;
ernl=0.5*l80mm-0.25*l5mm+60;     % From letter Ulf Sandberg to Peter Cenek 16 June 92.
lma_mm=0.001*10.^(lma/20);       % Convert texture measurements from dB to mm.
lme_mm=0.001*10.^(lme/20);
l5mm_mm=0.001*10.^(l5mm/20);
l80mm_mm=0.001*10.^(l80mm/20);

% Calculate MPD, ETD (and RMS) as decribed in ISO Standard 13473-1.
% The method consists of:
% 1. Low-pass filter at 400 cycles per meter (2.5mm wavelength).
% 2. Divide data into segment lengths of 100mm (baseline limiting).
% 3.. Detrend (suppress slope) of each segment.
% 4. Calculate the peak level for each segment ( being the average of the peaks in
%     two 50mm subsegments).
% 5. Calculate the Mean Profile Depth (MPD) for each segment, which is the segment peak
%     level (as above) minus the segment profile average.
% 6. Calculate the Estimated Texture Depth (ETD) for each segment, using:
%          ETD = 0.2 + 0.8 * MPD
```

```
% 7. Calculate the standard deviation (RMS) for each segment.
% 8. Calculate average values of MPD, ETD, and RMS for the whole profile.


% Low-pass filter for calculation of MPD, ETD & RMS.

filterwavelength=2.5;                          % (mm)
filterfreq=vel/filterwavelength;               % (Hz)
[b1,a1]=butter(16,filterfreq/(fsamp/2));       % 16th order Butterworth low-pass filter.
datafilt=filtfilt(b1,a1,datamm);               % Zero-phase filtering.


ns100mm=floor(nsamples/(testlength/100));      % No. of samples per 100mm.
ns50mm=floor(ns100mm/2);                       % No. of samples per 50mm.
nsegments=floor(nsamples/ns100mm);             % No. of 100mm segments.
datasegs=reshape(datafilt(1:ns100mm*nsegments),ns100mm,nsegments); % Reshape into
                                               % columns of 100mm segments.
clear datafilt
datasegs=detrend(datasegs);                    % Detrend each 100mm segment. Note
                                               % that detrend removes the mean.
peak1=max(datasegs(1:ns50mm,:));               % Peaks for first 50mm of each segment.
peak2=max(datasegs((ns50mm+1):ns100mm,:));     % Peaks for second 50mm of each segment.
peakave=mean([peak1;peak2]);                   % Averages of first & second peaks.
mpdmean=mean(peakave);                         % Detrended mean height is zero. Therefore
                                               % no need to subtract it.
etdmean=0.2+0.8*mpdmean;
rmsmean=mean(std(datasegs));              % Average standard deviation of each segment.
mpdstd=std(peakave);                      % Standard deviation of the invividual MPD values.

% Save individual 100mm mpd values to 'infile'.mpd file.
eval(['fid = fopen(''',infile,'.mpd'',''w'');']);
fprintf(fid,'%6.3f\n',peakave);
fclose(fid);

% Set plot text labels.

label1=['Data File: ',infname,'  p1/3'];
label2=['Analysed ',datetime];
label3=['Data File: ',infname,'  p2/3'];
label4=['Data File: ',infname,'  p3/3'];

figure(1)
clf

% Print header, site details, measurement details.

subplot(3,1,1)
axis('off')
text(0.18,1.2,'LASER PROFILOMETER','fontsize',13)
text(0,1.1,'ROAD PROFILE MEASUREMENT AND ANALYSIS','fontsize',13)
text(0,1.0,['OPUS INTERNATIONAL CONSULTANTS, CENTRAL LABORATORIES,',...
    '      ',program],'fontsize',7)
text(0.75,1.2,label1,'fontsize',10)
text(0.75,1.1,label2,'fontsize',10)
text(0,0.8,['Test Date : ',testdate],'fontsize',10)
text(0,0.7,['Site Identification : ',siteid],'fontsize',10)
text(0,0.6,['Wheelpath : ',wheelpath],'fontsize',10)
text(0,0.5,['Site Description : ',description],'fontsize',10)
text(0,0.4,['Comments : ',comments],'fontsize',10)
text(0,0.3,['Operator : ',operator],'fontsize',10)
text(0,0.1,['Test section length : ',num2str(endsep),...
    ' mm    Traverse speed : ',num2str(vel),' mm/s'],'fontsize',10)
text(0,0.0,['Traverse speed variation (%) : ',num2str(potnonlin)],'fontsize',10)
if potnonlin<1
    text(0.6,0.0,'ok  <1%','fontsize',10)
else
    text(0.6,0.0,'WARNING  >1%')
end
text(0,-0.1,['Sampled ',num2str(nsamples),' points @ ',num2str(fsamp),...
    ' Hz'],'fontsize',10)
text(0,-0.2,['Maximum voltage : ',num2str(vmax),...
    '           Minimum voltage : ',num2str(vmin)],'fontsize',10)
if vmax<9.995 & vmin>0.005
    text(0.6,-0.2,'ok','fontsize',10)
else
    text(0.6,-0.2,'WARNING   OUT OF RANGE')
end
text(0,-0.3,['Possible invalid data (%) : ',num2str(droppercent)],'fontsize',10)
if droppercent>10
    text(0.6,-0.3,'WARNING   >10%')
 end
text(0,-0.4,'Effect of overall slope has been removed from all height analysis.',...
    'fontsize',10)
text(0,-0.5,['Mean height : ',num2str(datamean),' mm              Std dev height: ',...
    num2str(datastd),' mm'],'fontsize',10)
text(0,-0.6,['Maximum height : ',num2str(datamax),' mm      Minimum height: ',...
    num2str(datamin),' mm'],'fontsize',10)
```

```
% Plot profile of first 160mm of data.

subplot(3,1,2)
xind=find(distmm>=160);
plot(distmm(1:xind(1)),datamm(1:xind(1)))
clear xind
set(gca,'aspectratio',[(163.5/33),nan])      % 163.5mm is default box width.
axis([0 163.5 0 33.0]);                       % Choose to plot 33mm height.
title(['Section of measured profile - first 160mm']);
ylabel('Height (mm)');
xlabel('Distance (mm) ');


% List measured statistics and noise analysis.

subplot(3,1,3)
axis('off')
text(0,1.1,['Pavement texture measurements '],'fontsize',12)
text(0,1.0,['Lma :     ',num2str(lma),' dB(Ma)      (',num2str(lma_mm),...
    ' mm rms)'],'fontsize',10)
text(0.5,1.0,['Lme :     ',num2str(lme),' dB(Me)          (',num2str(lme_mm),...
    ' mm rms)'],'fontsize',10)
text(0,0.9,['L5mm : ',num2str(l5mm),' dB(5mm)   (',num2str(l5mm_mm),...
    ' mm rms)'],'fontsize',10)
text(0.5,0.9,['L80mm : ',num2str(l80mm),' dB(80mm)   (',num2str(l80mm_mm),...
    ' mm rms)'],'fontsize',10)
text(0,0.8,['Tdma :   ',num2str(tdma),' mm'],'fontsize',10)
text(0.5,0.8,['ERNL :    ',num2str(ernl),' dB(A)'],'fontsize',10)
text(0,0.6,['Mean Profile Depth analysis to ISO Standard 13473-1'],'fontsize',12)
text(0,0.5,['The following measurements based on the average of ',...
    num2str(nsegments),' segments of 100 mm.'],'fontsize',10)
text(0,0.4,['MPD : ',num2str(mpdmean),' mm      ETD : ',num2str(etdmean),...
    ' mm          RMS : ',num2str(rmsmean),     ' mm'],'fontsize',10)
text(0,0.3,['Standard deviation of individual MPD values : ',num2str(mpdstd),...
    ' mm'],'fontsize',10)


eval(['print ',infile,'.ps'])     % Save the figures to .ps file.


figure(2)
clf

% Plot averaged profile spectrum.

subplot(3,1,1)
loglog(f3lambda,p3);
axis([0.5 600 0.01 10])
set(gca,'aspectratio',[2,nan])
set(gca,'xdir','reverse');      % Set x-axis to increase from right to left.
xlabel('Texture Wavelength (mm)')
ylabel('(n.Sn)^0.5  (mm)')
set(gca,'xticklabels',[100 1 10])      % I don't know why [100 10 1] isn't correct!
set(gca,'yticklabels',[0.01 0.1 1 10])
text(0.85,1.2,label3,'units','normalized','fontsize',10)
text(0.85,1.1,label2,'units','normalized','fontsize',10)
text(0.03,0.11,[num2str(nfft),' point psd'],'units','normalized','fontsize',8);
text(0.03,0.06,[num2str(nav),' pts av.'],'units','normalized','fontsize',8);


% List third-octave band spectral levels.

obdb1dp=(round(10*obdb))/10;    % Print to 1 decimal place.

subplot(3,1,2)
axis('off')
text(0.25,1.1,['Third-Octave Band Spectral Levels'],'fontsize',12)
text(0.2,1.0,['Wavelengths and texture levels (dB relative to 0.001 mm std)']...
    ,'fontsize',10)
text(0.1,0.8,['500 mm   ',num2str(obdb1dp(1)),' dB'],'fontsize',10)
text(0.1,0.7,['400 mm   ',num2str(obdb1dp(2)),' dB'],'fontsize',10)
text(0.1,0.6,['315 mm   ',num2str(obdb1dp(3)),' dB'],'fontsize',10)
text(0.1,0.5,['250 mm   ',num2str(obdb1dp(4)),' dB'],'fontsize',10)
text(0.1,0.4,['200 mm   ',num2str(obdb1dp(5)),' dB'],'fontsize',10)
text(0.1,0.3,['160 mm   ',num2str(obdb1dp(6)),' dB'],'fontsize',10)
text(0.1,0.2,['125 mm   ',num2str(obdb1dp(7)),' dB'],'fontsize',10)
text(0.1,0.1,['100 mm   ',num2str(obdb1dp(8)),' dB'],'fontsize',10)
text(0.1,0.0,[' 80 mm   ',num2str(obdb1dp(9)),' dB'],'fontsize',10)
text(0.1,-0.1,[' 63 mm   ',num2str(obdb1dp(10)),' dB'],'fontsize',10)
text(0.4,0.8,['50   mm   ',num2str(obdb1dp(11)),' dB'],'fontsize',10)
text(0.4,0.7,['40   mm   ',num2str(obdb1dp(12)),' dB'],'fontsize',10)
text(0.4,0.6,['31.5mm   ',num2str(obdb1dp(13)),' dB'],'fontsize',10)
text(0.4,0.5,['25   mm   ',num2str(obdb1dp(14)),' dB'],'fontsize',10)
text(0.4,0.4,['20   mm   ',num2str(obdb1dp(15)),' dB'],'fontsize',10)
text(0.4,0.3,['16   mm   ',num2str(obdb1dp(16)),' dB'],'fontsize',10)
text(0.4,0.2,['12.5mm   ',num2str(obdb1dp(17)),' dB'],'fontsize',10)
text(0.4,0.1,['10   mm   ',num2str(obdb1dp(18)),' dB'],'fontsize',10)
text(0.4,0.0,['8    mm   ',num2str(obdb1dp(19)),' dB'],'fontsize',10)
```

```
text(0.4,-0.1,['6.3 mm   ',num2str(obdbldp(20)),' dB'],'fontsize',10)
text(0.7,0.8,['5   mm   ',num2str(obdbldp(21)),' dB'],'fontsize',10)
text(0.7,0.7,['4   mm   ',num2str(obdbldp(22)),' dB'],'fontsize',10)
text(0.7,0.6,['3.15mm   ',num2str(obdbldp(23)),' dB'],'fontsize',10)
text(0.7,0.5,['2.5 mm   ',num2str(obdbldp(24)),' dB'],'fontsize',10)
text(0.7,0.4,['2   mm   ',num2str(obdbldp(25)),' dB'],'fontsize',10)
text(0.7,0.3,['1.6 mm   ',num2str(obdbldp(26)),' dB'],'fontsize',10)
text(0.7,0.2,['1.25mm   ',num2str(obdbldp(27)),' dB'],'fontsize',10)
text(0.7,0.1,['1   mm   ',num2str(obdbldp(28)),' dB'],'fontsize',10)
text(0.7,0.0,['0.8 mm   ',num2str(obdbldp(29)),' dB'],'fontsize',10)
text(0.7,-0.1,['0.63mm   ',num2str(obdbldp(30)),' dB'],'fontsize',10)


% Plot wavelength third-octave band spectrum.

subplot(3,1,3)
[xb,yb]=bar_m1(lambda,obdb);     % Converts normal x,y to xb,yb values for bar chart.
semilogx(xb,yb)
axis([0.5 600 20 70])
set(gca,'aspectratio',[2,nan])
set(gca,'xdir','reverse');     % Set x-axis to increase from right to left.
xlabel('Texture Wavelength (mm)')
ylabel('dB')
set(gca,'xticklabels',[100 1 10])     % I don't know why [100 10 1] isn't correct!
eval(['print ',infile,'.ps -append'])    % Save the figures to .ps file.


figure(3)
clf

% Plot raw voltages.

subplot(2,1,1)
plot(datv)
axis([0 7500 0 10])
set(gca,'aspectratio',[1.6,nan])
xlabel('Sample Number')
ylabel('Volts')
title('Original Data')
text(0.75,1.15,label4,'units','normalized','fontsize',10)
text(0.75,1.1,label2,'units','normalized','fontsize',10)

% Plot measured road profile.

subplot(2,1,2)
plot(distmm,datamm)
set(gca,'aspectratio',[1.6,nan])
xlabel('Distance (mm)')
ylabel('Height (mm)')
title('Measured Profile')
eval(['print ',infile,'.ps -append'])     % Save the figures to .ps file.

% End of data file analysis.


% Now get inputs for next data file if using .pcf file.

if pcf=='y' & anothertest=='y'
    % Read inputs for second and subsequent data files.
    anothertest=fscanf(readpcf,'%s',1);      % get y/n  Process another test?
    if anothertest~='y',break,end
    infname=fscanf(readpcf,'%s',1);
    nn=length(infname);
    i=1;                          % find position of "." in the filename.
    while ((infname(i+1)~='.') & (i~=nn))
       i=i+1;
    end
    infile=infname(1:i);          % infile is infname without the extension.
    endsep=fscanf(readpcf,'%f/n');
    testdate=fgetl(readpcf);
    siteid=fgetl(readpcf);
    wheelpath=fgetl(readpcf);
    description=fgetl(readpcf);
    comments=fgetl(readpcf);
    operator=fgetl(readpcf);

else anothertest='n';
end


end %*********************** END OF MAIN LOOP ***********************************

disp ' '
disp ' End of ROADPRO2'
```

APPENDIX 2
EXAMPLES OF SURFACE PROFILE ANALYSIS USING *ROADPRO2*

EXAMPLES OF SURFACE PROFILE ANALYSIS USING *ROADPRO2*

The following pages present seven different examples of output from *ROADPRO2* for a range of surface profiles. There are a number of noteworthy features of these printouts.

Example No.	*Site Description*
1.	Medium chipseal *(file chipa.dat).*
2.	Smooth concrete *(file conca.dat).* Note that there were no invalid measurements in this data file but the surface is quite smooth, and so the invalid data search routine has identified a high proportion of the data as being possibly invalid and has printed a warning.
3.	Polished flat stone bench *(file bench.dat).* Again there were no invalid measurements in the data file, but the surface is so smooth that almost all the data have been identified as being possibly invalid. These are the same data that are shown in Figure 6.1 in this report. The measurements for this polished surface provide an indication of the extent to which background noise is present in the measured data, e.g. MPD for this surface is theoretically zero but has been measured as 0.022 mm.
4.	Perforated metal plate *(file lmesha.dat).* This profile was tested as a demonstration of a surface for which a high proportion of invalid measurements do occur. The laser has not been able to obtain valid measurements for the holes in the plate. A characteristic pattern can be seen in the section of the measured profile. This commonly consists of an arbitrary constant height being measured for each hole, followed by a sharp downward spike. This difference between the measured profile at the beginning and end of each hole has no apparent physical explanation, and is therefore believed to be a characteristic of the laser operation.
5.	Machined triangular calibration profile *(file txtur10a.dat).* This profile has a triangular wavelength of 20 mm and height of 10 mm. This profile has a theoretical third octave band spectral level of 69.1 dB at 20 mm wavelength. It may be seen from the analysis that this value has been measured correctly. This is an important calibration check.

The measured spectrum has some significant differences to the theoretical spectra discussed in 6 and 7 below. This is largely related to the short length of the triangular calibration profile data (480 mm), combined with some minor effects caused by imperfections in the machining of the profile, laser spot size, and measurement error.

6. Theoretical triangular profile *(file trianxx.dat).*
This is not a measured profile; the data have been generated mathematically.

Note that the calculated psd has very much more precisely defined harmonic frequencies than the measured profile, and that these frequencies fall into specific third octave band, producing an irregular pattern for the third octave band spectral levels.

The calculated third octave band spectral level for 20 mm wavelength is again 69.1 dB for a 10 mm peak-to-peak amplitude waveform.

7. Theoretical sinusoidal profile *(file sinexx.dat).*
This is not a measured profile; the data have been generated mathematically.

The calculated third octave band spectral level for 20 mm wavelength is 71.0 dB for a 10 mm peak-to-peak amplitude waveform.

EXAMPLE 1

LASER PROFILOMETER
ROAD PROFILE MEASUREMENT AND ANALYSIS

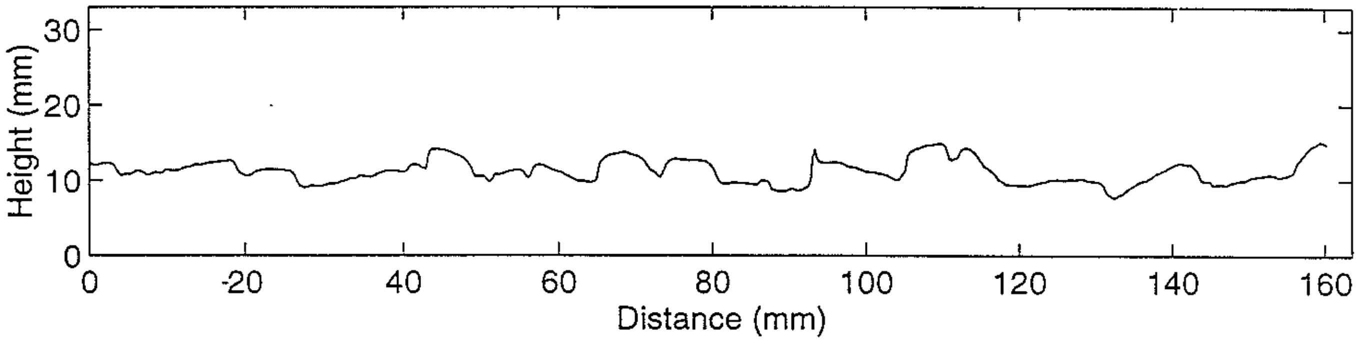
Data File: chipa.dat p1/2
Analysed 3-Dec-96 15:7

WORKS CONSULTANCY SERVICES LTD, CENTRAL LABORATORIES, roadpro.m version 3-December-1996

Test Date : 20 May 96
Site Identification : Central Laboratories outside Shed 12
Wheelpath :
Site Description : Medium Chipseal
Comments :
Operator : Doug Brown

Test section length : 1657 mm Traverse speed : 149 mm/s
Traverse speed variation (%) : 0.7992 ok <1%
Sampled 5560 points @ 500 Hz
Maximum voltage : 6.826 Minimum voltage : 2.029 ok
Possible invalid data (%) : 1.637
Effect of overall slope has been removed from all height analysis.
Mean height : 14.85 mm Std dev height: 3.174 mm
Maximum height : 22.63 mm Minimum height: 7.703 mm

Section of measured profile - first 160mm

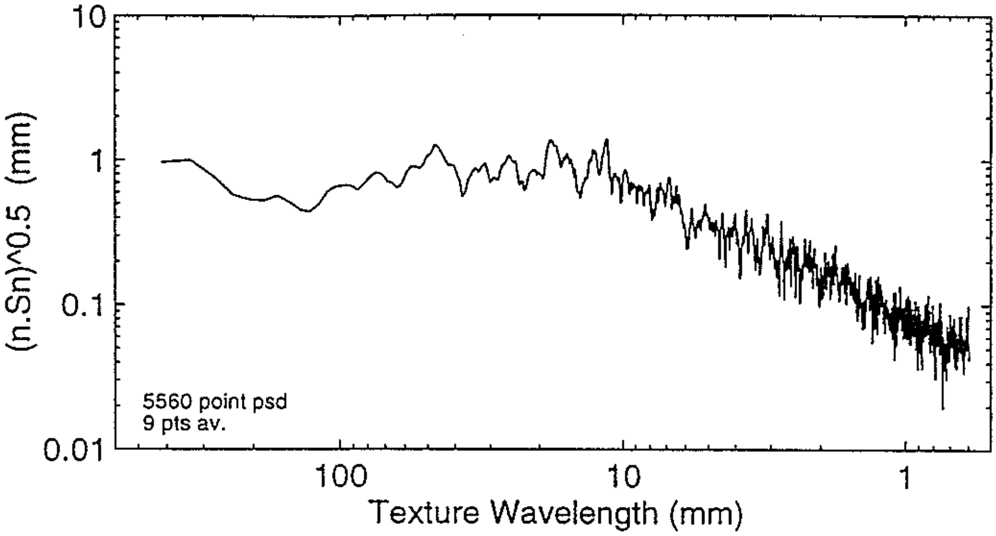


Pavement texture measurements

Lma :	63.29 dB(Ma)	(1.46 mm rms)	Lme :	60.9 dB(Me)	(1.109 mm rms)
L5mm :	51.17 dB(5mm)	(0.3618 mm rms)	L80mm :	55.63 dB(80mm)	(0.6044 mm rms)
Tdma :	3.159 mm		ERNL :	75.02 dB(A)	

Mean Profile Depth analysis to ISO Standard 13473-1

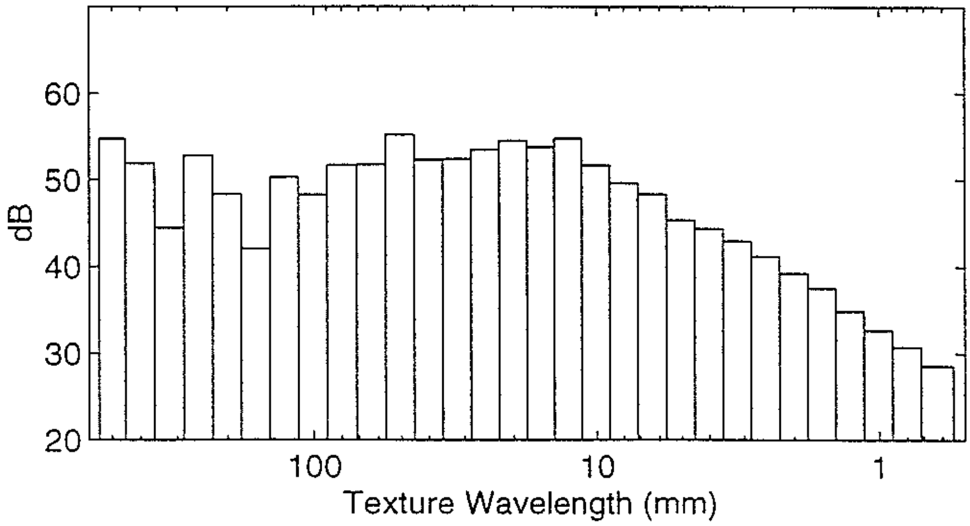
The following measurements based on the average of 16 segments of 100 mm.
MPD : 3.213 mm ETD : 2.77 mm RMS : 1.566 mm
Standard deviation of individual MPD values : 0.4251 mm



Third-Octave Band Spectral Levels

Wavelengths and texture levels (dB relative to 0.001 mm std)

500 mm	54.8 dB	50 mm	55.2 dB	5 mm	45.4 dB
400 mm	51.9 dB	40 mm	52.3 dB	4 mm	44.4 dB
315 mm	44.5 dB	31.5mm	52.4 dB	3.15mm	43 dB
250 mm	52.8 dB	25 mm	53.5 dB	2.5 mm	41.2 dB
200 mm	48.4 dB	20 mm	54.5 dB	2 mm	39.3 dB
160 mm	42 dB	16 mm	53.8 dB	1.6 mm	37.6 dB
125 mm	50.3 dB	12.5mm	54.8 dB	1.25mm	34.9 dB
100 mm	48.3 dB	10 mm	51.7 dB	1 mm	32.7 dB
80 mm	51.7 dB	8 mm	49.6 dB	0.8 mm	30.8 dB
63 mm	51.8 dB	6.3 mm	48.4 dB	0.63mm	28.6 dB



EXAMPLE 2

LASER PROFILOMETER
ROAD PROFILE MEASUREMENT AND ANALYSIS

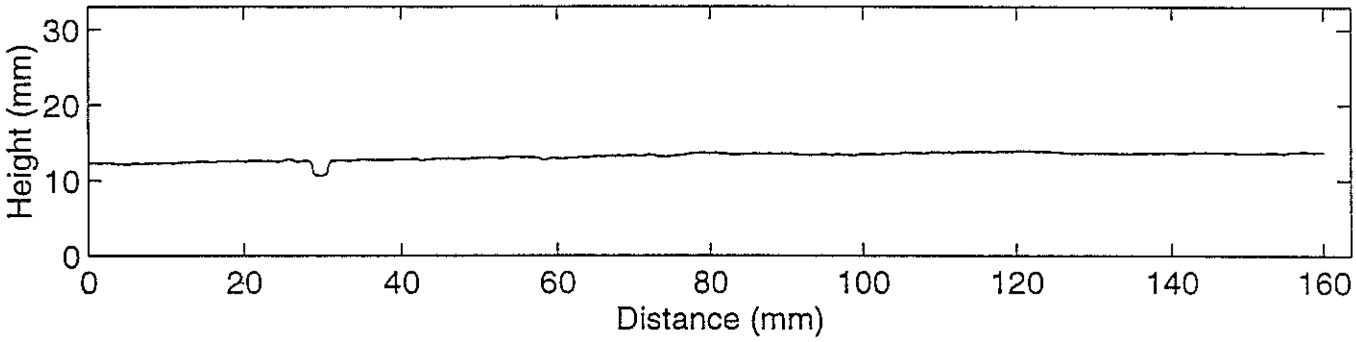
Data File: conca.dat p1/2
Analysed 3-Dec-96 15:8

WORKS CONSULTANCY SERVICES LTD, CENTRAL LABORATORIES, roadpro.m version 3-December-1996

Test Date : 20 May 96
Site Identification : Central Laboratories outside Shed 12
Wheelpath :
Site Description : Smooth Concrete
Comments :
Operator : Doug Brown

Test section length : 1657 mm Traverse speed : 146.7 mm/s
Traverse speed variation (%) : 0.8911 ok <1%
Sampled 5649 points @ 500 Hz
Maximum voltage : 5.918 Minimum voltage : 3.626 ok
Possible invalid data (%) : 17.26 WARNING >10%
Effect of overall slope has been removed from all height analysis.
Mean height : 15.67 mm Std dev height: 1.616 mm
Maximum height : 18.61 mm Minimum height: 10.6 mm

Section of measured profile - first 160mm



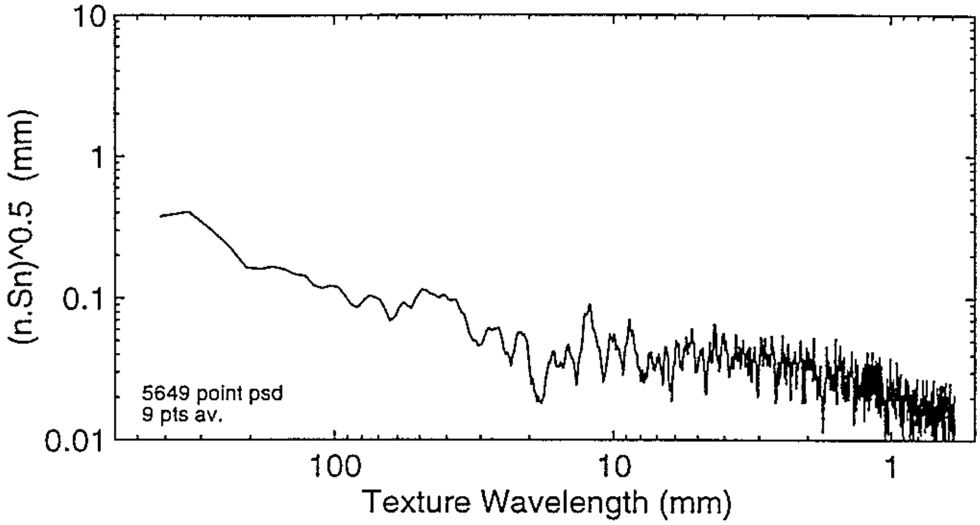
Pavement texture measurements

Lma : 40.94 dB(Ma) (0.1114 mm rms)
L5mm : 31.32 dB(5mm) (0.03681 mm rms)
Tdma : 0.0563 mm

Lme : 54.13 dB(Me) (0.509 mm rms)
L80mm : 38.22 dB(80mm) (0.08149 mm rms)
ERNL : 71.28 dB(A)

Mean Profile Depth analysis to ISO Standard 13473-1

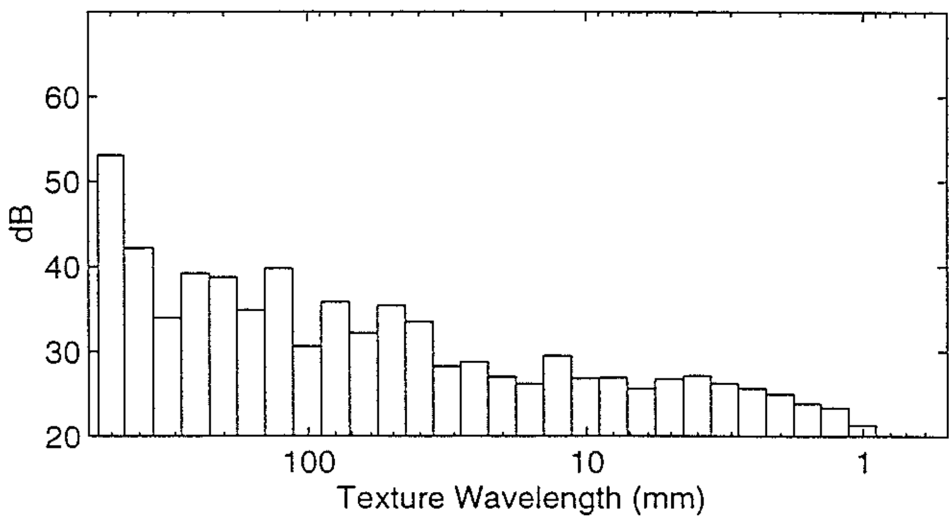
The following measurements based on the average of 16 segments of 100 mm.
MPD : 0.2824 mm ETD : 0.4259 mm RMS : 0.1498 mm
Standard deviation of individual MPD values : 0.06909 mm



Third-Octave Band Spectral Levels

Wavelengths and texture levels (dB relative to 0.001 mm std)

500 mm	53.1 dB	50 mm	35.4 dB	5 mm	26.8 dB
400 mm	42.2 dB	40 mm	33.5 dB	4 mm	27.1 dB
315 mm	34 dB	31.5mm	28.3 dB	3.15mm	26.2 dB
250 mm	39.2 dB	25 mm	28.8 dB	2.5 mm	25.6 dB
200 mm	38.8 dB	20 mm	27 dB	2 mm	25 dB
160 mm	34.9 dB	16 mm	26.2 dB	1.6 mm	23.8 dB
125 mm	39.8 dB	12.5mm	29.5 dB	1.25mm	23.4 dB
100 mm	30.6 dB	10 mm	26.8 dB	1 mm	21.3 dB
80 mm	35.8 dB	8 mm	26.9 dB	0.8 mm	19.6 dB
63 mm	32.2 dB	6.3 mm	25.6 dB	0.63mm	18 dB



EXAMPLE 3

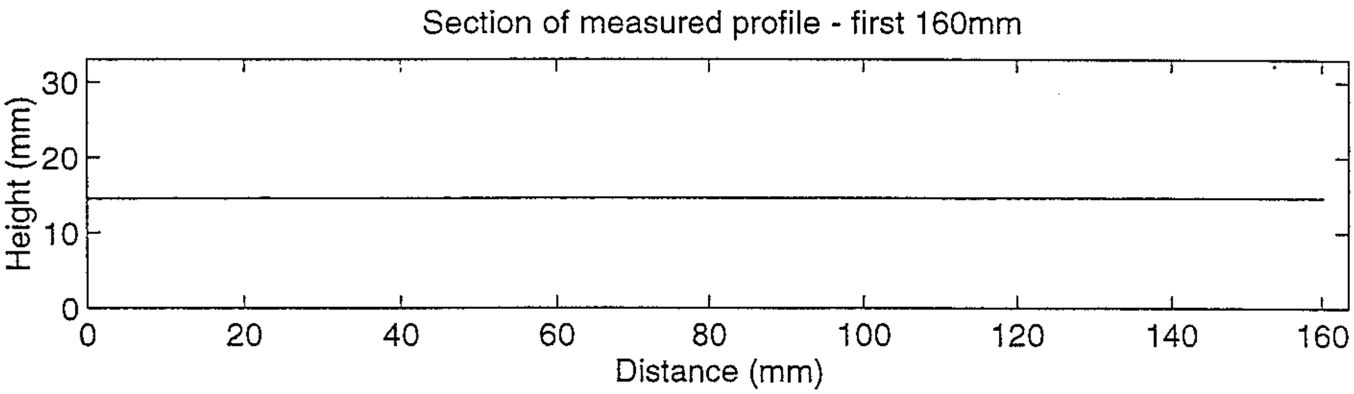
LASER PROFILOMETER
ROAD PROFILE MEASUREMENT AND ANALYSIS

Data File: bench.dat p1/2
Analysed 3-Dec-96 15:10

WORKS CONSULTANCY SERVICES LTD, CENTRAL LABORATORIES, roadpro.m version 3-December-1996

Test Date : 2 May 96
Site Identification : Central Laboratories workshop
Wheelpath :
Site Description : Polished flat stone bench
Comments :
Operator : Doug Brown

Test section length : 1657 mm   Traverse speed : 141.8 mm/s
Traverse speed variation (%) : 0.9258   ok <1%
Sampled 5841 points @ 500 Hz
Maximum voltage : 4.539   Minimum voltage : 4.382   ok
Possible invalid data (%) : 91.3   WARNING >10%
Effect of overall slope has been removed from all height analysis.
Mean height : 14.68 mm   Std dev height: 0.05712 mm
Maximum height : 14.81 mm   Minimum height: 14.52 mm

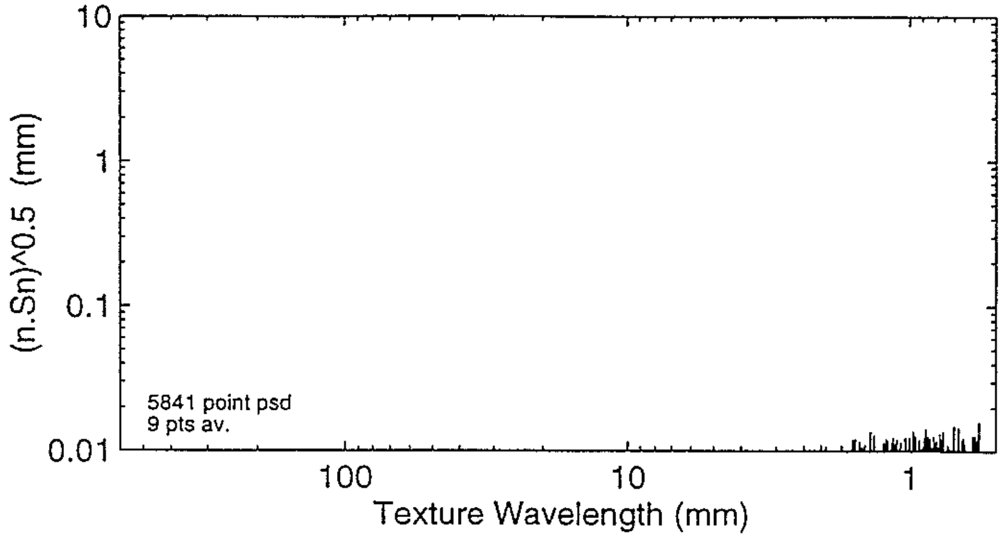


Pavement texture measurements

Lma : 19.45 dB(Ma) (0.009383 mm rms)   Lme : 13.98 dB(Me) (0.005001 mm rms)
L5mm : 13.78 dB(5mm) (0.004888 mm rms)   L80mm : 5.652 dB(80mm) (0.001917 mm rms)
Tdma : -0.1784 mm   ERNL : 59.38 dB(A)

Mean Profile Depth analysis to ISO Standard 13473-1

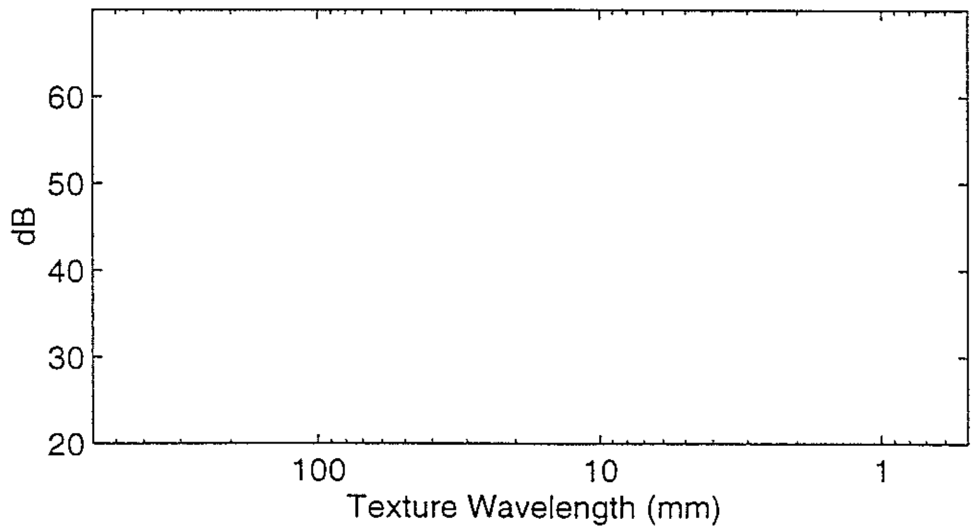
The following measurements based on the average of 16 segments of 100 mm.
MPD : 0.02171 mm   ETD : 0.2174 mm   RMS : 0.008913 mm
Standard deviation of individual MPD values : 0.003589 mm



Third-Octave Band Spectral Levels

Wavelengths and texture levels (dB relative to 0.001 mm std)

500 mm	8.3 dB	50 mm	0.8 dB	5 mm	9.1 dB
400 mm	5 dB	40 mm	-1.2 dB	4 mm	9.4 dB
315 mm	1.8 dB	31.5mm	2.8 dB	3.15mm	11.3 dB
250 mm	4.7 dB	25 mm	-0.2 dB	2.5 mm	11.6 dB
200 mm	1.9 dB	20 mm	4.6 dB	2 mm	11.4 dB
160 mm	3.4 dB	16 mm	3.5 dB	1.6 mm	12.5 dB
125 mm	5.2 dB	12.5mm	6.7 dB	1.25mm	13 dB
100 mm	1.6 dB	10 mm	4 dB	1 mm	13.2 dB
80 mm	0.3 dB	8 mm	7.1 dB	0.8 mm	13.3 dB
63 mm	0.7 dB	6.3 mm	8.5 dB	0.63mm	13.2 dB



LASER PROFILOMETER
ROAD PROFILE MEASUREMENT AND ANALYSIS

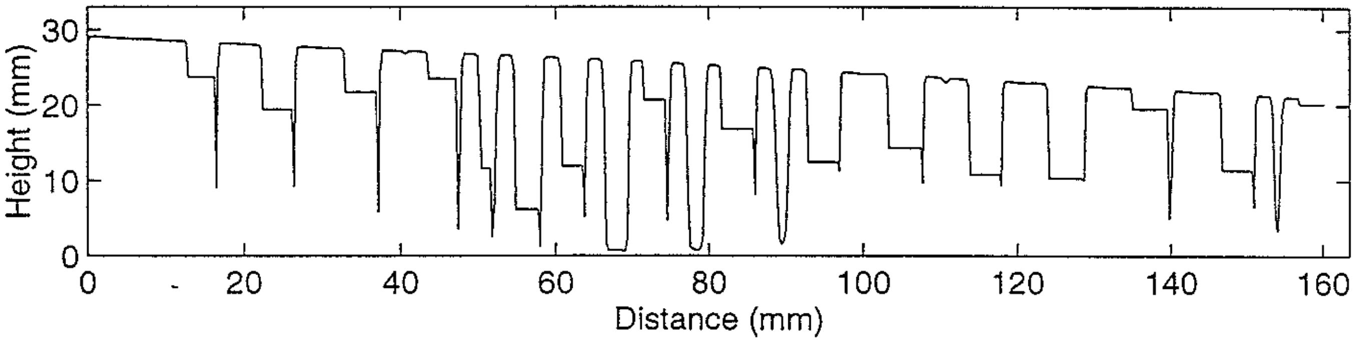
Data File: lmesha.dat p1/2
Analysed 3-Dec-96 15:11

WORKS CONSULTANCY SERVICES LTD, CENTRAL LABORATORIES, roadpro.m version 3-December-1996

Test Date : 20 May 96
Site Identification : Central Laboratories
Wheelpath :
Site Description : Perforated metal plate, 4.5mm hole diameter
Comments :
Operator : Doug Brown

Test section length : 1203 mm Traverse speed : 143 mm/s
Traverse speed variation (%) : 0.8122 ok <1%
Sampled 4205 points @ 500 Hz
Maximum voltage : 9.922 Minimum voltage : 0.0171 ok
Possible invalid data (%) : 46.97 WARNING >10%
Effect of overall slope has been removed from all height analysis.
Mean height : 14.75 mm Std dev height: 6.389 mm
Maximum height : 32 mm Minimum height: 0.03942 mm

Section of measured profile - first 160mm



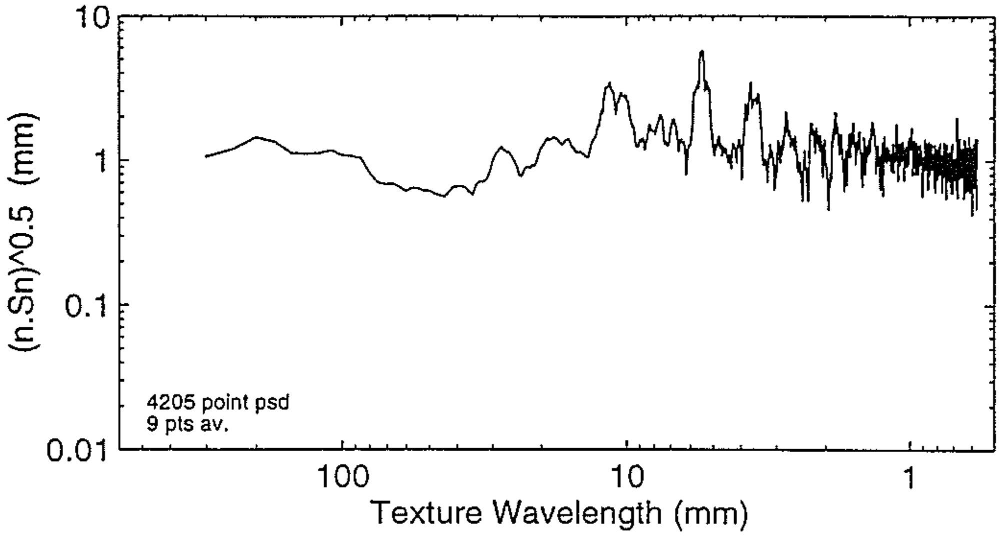
Pavement texture measurements

Lma : 70.54 dB(Ma) (3.364 mm rms)
L5mm : 66.92 dB(5mm) (2.219 mm rms)
Tdma : 7.538 mm

Lme : 66.35 dB(Me) (2.077 mm rms)
L80mm : 57.79 dB(80mm) (0.7749 mm rms)
ERNL : 72.16 dB(A)

Mean Profile Depth analysis to ISO Standard 13473-1

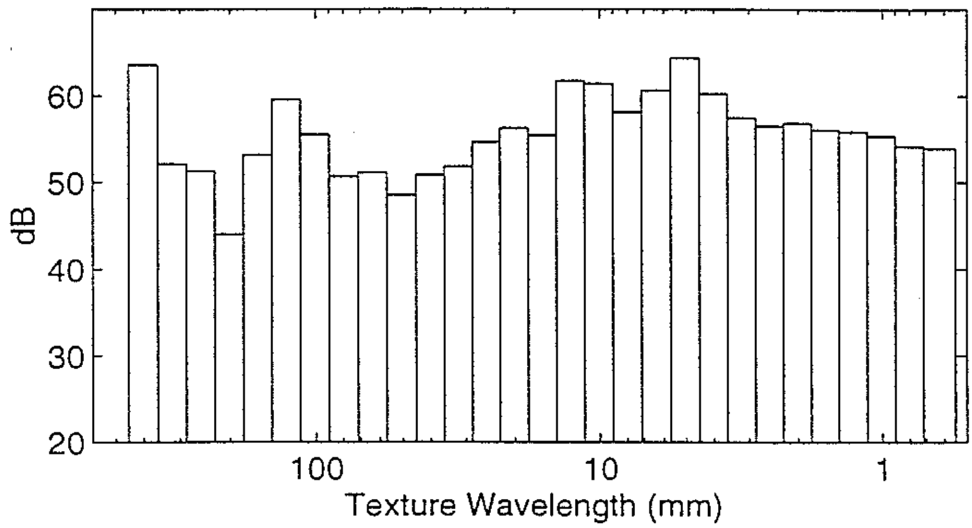
The following measurements based on the average of 12 segments of 100 mm.
MPD : 4.944 mm ETD : 4.155 mm RMS : 3.747 mm
Standard deviation of individual MPD values : 2.283 mm



Third-Octave Band Spectral Levels

Wavelengths and texture levels (dB relative to 0.001 mm std)

500 mm	0 dB	50 mm	48.6 dB	5 mm	64.4 dB
400 mm	63.6 dB	40 mm	50.9 dB	4 mm	60.2 dB
315 mm	52.1 dB	31.5mm	51.9 dB	3.15mm	57.4 dB
250 mm	51.3 dB	25 mm	54.6 dB	2.5 mm	56.5 dB
200 mm	44 dB	20 mm	56.2 dB	2 mm	56.8 dB
160 mm	53.2 dB	16 mm	55.4 dB	1.6 mm	56.1 dB
125 mm	59.6 dB	12.5mm	61.7 dB	1.25mm	55.9 dB
100 mm	55.5 dB	10 mm	61.4 dB	1 mm	55.4 dB
80 mm	50.7 dB	8 mm	58.1 dB	0.8 mm	54.2 dB
63 mm	51.1 dB	6.3 mm	60.6 dB	0.63mm	54 dB



LASER PROFILOMETER
ROAD PROFILE MEASUREMENT AND ANALYSIS

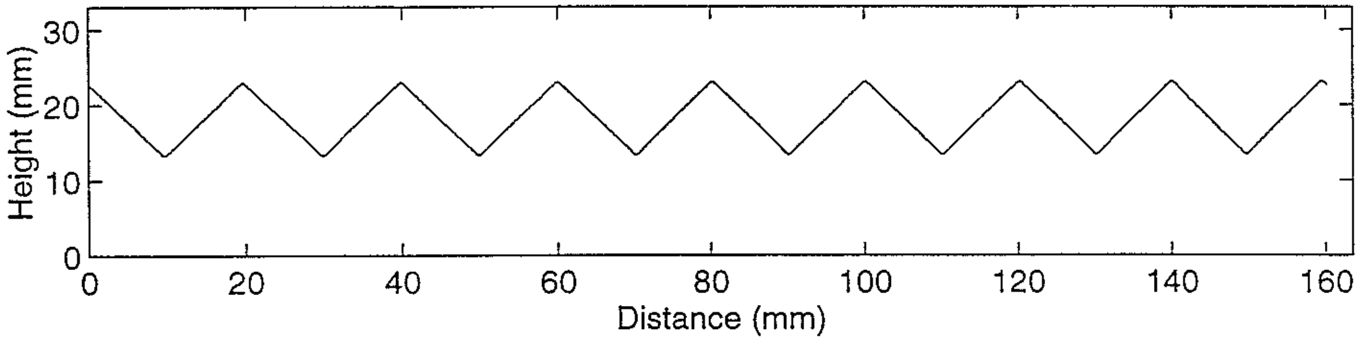
Data File: txtur10a.dat p1/2
Analysed 3-Dec-96 15:5

WORKS CONSULTANCY SERVICES LTD, CENTRAL LABORATORIES, roadpro.m version 3-December-1996

Test Date : 4 Oct 96
Site Identification : SH1 south of Plimmerton
Wheelpath :
Site Description : Machined triangular calibration profile
Comments :
Operator : Doug Brown

Test section length : 480 mm   Traverse speed : 145.4 mm/s
Traverse speed variation (%) : 0.2651   ok <1%
Sampled 1651 points @ 500 Hz
Maximum voltage : 7.207   Minimum voltage : 3.855   ok
Possible invalid data (%) : 0
Effect of overall slope has been removed from all height analysis.
Mean height : 18.2 mm   Std dev height: 2.877 mm
Maximum height : 23.16 mm   Minimum height: 13.17 mm

Section of measured profile - first 160mm



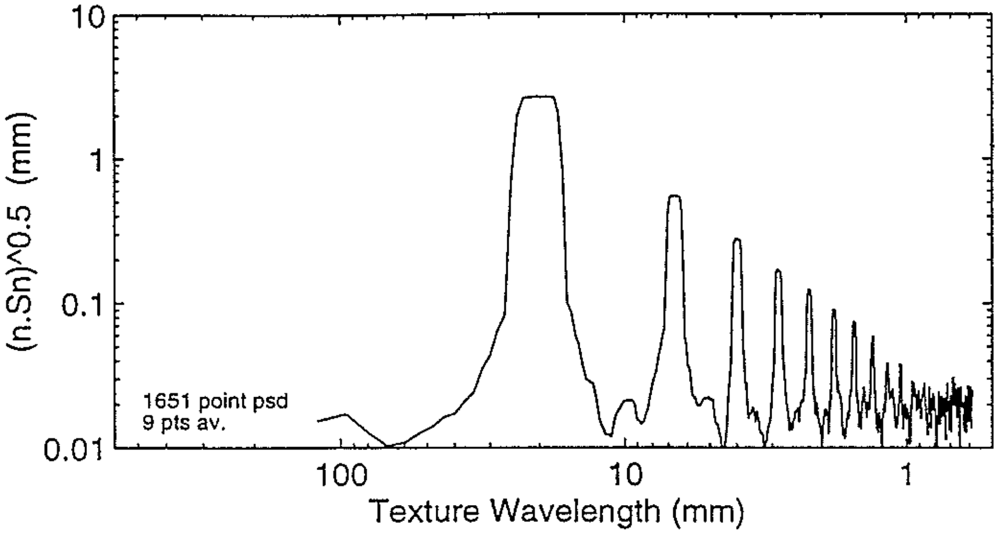
Pavement texture measurements

Lma : 69.17 dB(Ma) (2.874 mm rms)
L5mm : 50.57 dB(5mm) (0.3375 mm rms)
Tdma : 6.41 mm

Lme : 35.88 dB(Me) (0.06224 mm rms)
L80mm : 17.34 dB(80mm) (0.007363 mm rms)
ERNL : 56.03 dB(A)

Mean Profile Depth analysis to ISO Standard 13473-1

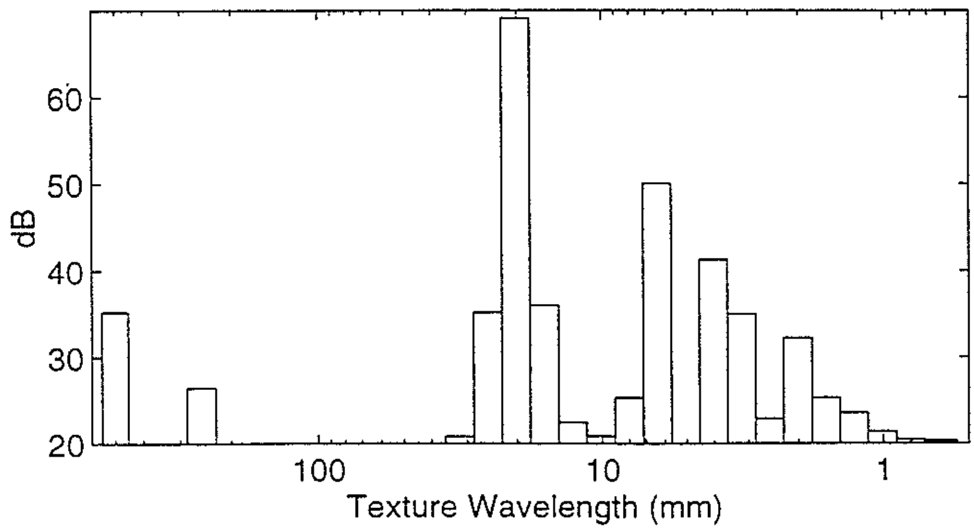
The following measurements based on the average of 4 segments of 100 mm.
MPD : 4.813 mm   ETD : 4.05 mm   RMS : 2.861 mm
Standard deviation of individual MPD values : 0.01265 mm



Third-Octave Band Spectral Levels

Wavelengths and texture levels (dB relative to 0.001 mm std)

500 mm	35.2 dB	50 mm	17.7 dB	5 mm	19.7 dB
400 mm	0 dB	40 mm	17.5 dB	4 mm	41.3 dB
315 mm	0 dB	31.5mm	20.8 dB	3.15mm	35 dB
250 mm	26.5 dB	25 mm	35.2 dB	2.5 mm	22.9 dB
200 mm	0 dB	20 mm	69.1 dB	2 mm	32.2 dB
160 mm	15 dB	16 mm	36 dB	1.6 mm	25.3 dB
125 mm	8 dB	12.5mm	22.5 dB	1.25mm	23.6 dB
100 mm	12.7 dB	10 mm	20.9 dB	1 mm	21.4 dB
80 mm	12.6 dB	8 mm	25.3 dB	0.8 mm	20.5 dB
63 mm	12.4 dB	6.3 mm	50 dB	0.63mm	20.3 dB



EXAMPLE 6

LASER PROFILOMETER
ROAD PROFILE MEASUREMENT AND ANALYSIS

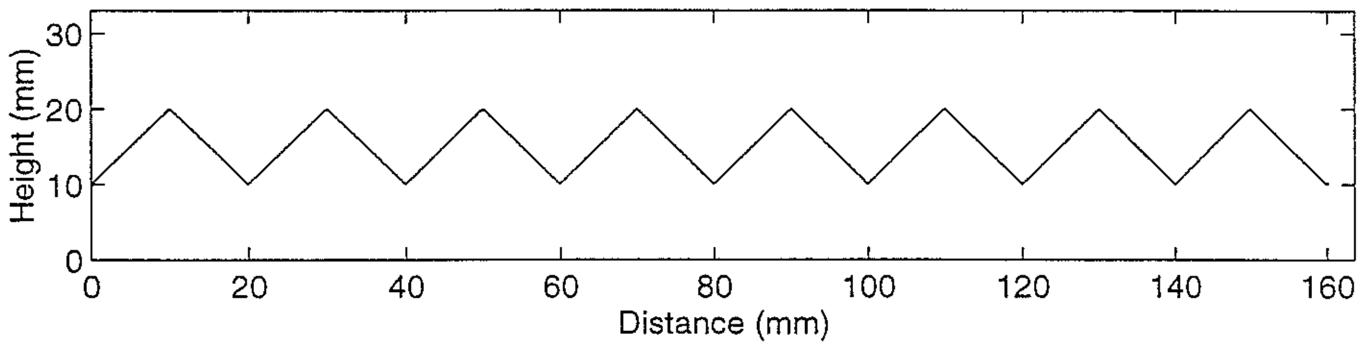
Data File: trianxx.dat p1/2
Analysed 3-Dec-96 15:13

WORKS CONSULTANCY SERVICES LTD, CENTRAL LABORATORIES, roadpro.m version 3-December-1996

Test Date : 3 Dec 96
Site Identification :
Wheelpath :
Site Description : Theoretical triangular profile
Comments :
Operator : Paul Carpenter

Test section length : 2000 mm Traverse speed : 100 mm/s
Traverse speed variation (%) : 0.004867 ok <1%
Sampled 1e+004 points @ 500 Hz
Maximum voltage : 6.115 Minimum voltage : 3.057 ok
Possible invalid data (%) : 0
Effect of overall slope has been removed from all height analysis.
Mean height : 15 mm Std dev height: 2.888 mm
Maximum height : 20 mm Minimum height: 9.999 mm

Section of measured profile - first 160mm



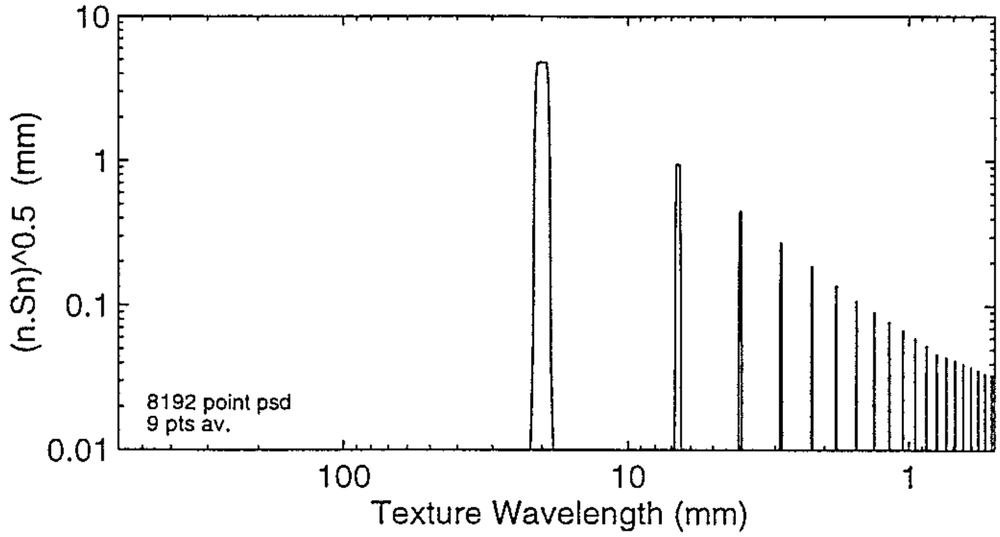
Pavement texture measurements

Lma : 69.21 dB(Ma) (2.887 mm rms)
L5mm : 50.62 dB(5mm) (0.3396 mm rms)
Tdma : 6.441 mm

Lme : -12.59 dB(Me) (0.0002346 mm rms)
L80mm : -46.14 dB(80mm) (4.929e-006 mm rms)
ERNL : 24.27 dB(A)

Mean Profile Depth analysis to ISO Standard 13473-1

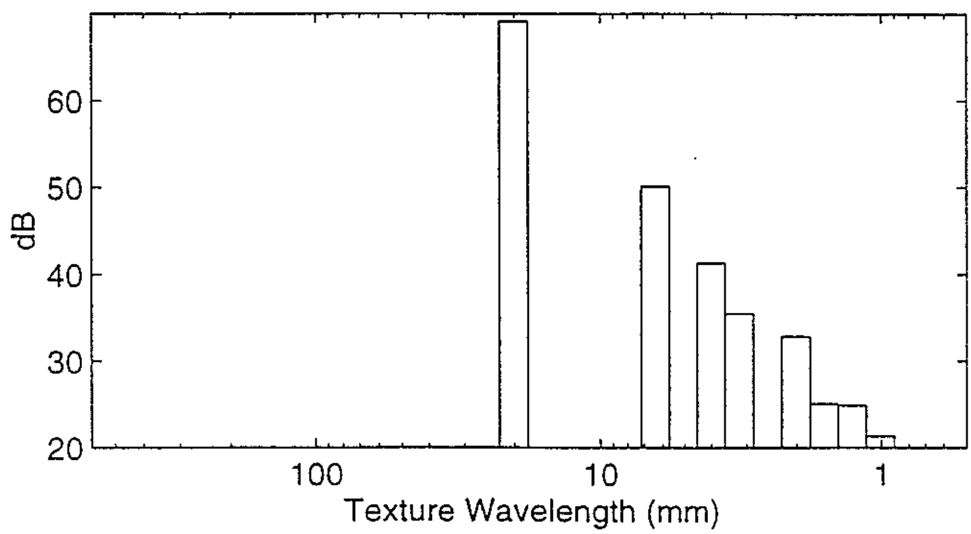
The following measurements based on the average of 20 segments of 100 mm.
MPD : 4.765 mm ETD : 4.012 mm RMS : 2.89 mm
Standard deviation of individual MPD values : 0.00006176 mm



Third-Octave Band Spectral Levels

Wavelengths and texture levels (dB relative to 0.001 mm std)

500 mm	-13.5 dB	50 mm	-47.3 dB	5 mm	-53.8 dB
400 mm	-21.4 dB	40 mm	-40.8 dB	4 mm	41.3 dB
315 mm	-27.4 dB	31.5mm	-32.1 dB	3.15mm	35.5 dB
250 mm	-30.9 dB	25 mm	-8 dB	2.5 mm	-21.9 dB
200 mm	-38.1 dB	20 mm	69.1 dB	2 mm	32.9 dB
160 mm	-43.6 dB	16 mm	-10.6 dB	1.6 mm	25.1 dB
125 mm	-46.9 dB	12.5mm	-37.7 dB	1.25mm	24.9 dB
100 mm	-50.4 dB	10 mm	-52.8 dB	1 mm	21.4 dB
80 mm	-51.9 dB	8 mm	-31.2 dB	0.8 mm	20 dB
63 mm	-50.6 dB	6.3 mm	50.1 dB	0.63mm	18.1 dB



EXAMPLE 7

LASER PROFILOMETER
ROAD PROFILE MEASUREMENT AND ANALYSIS

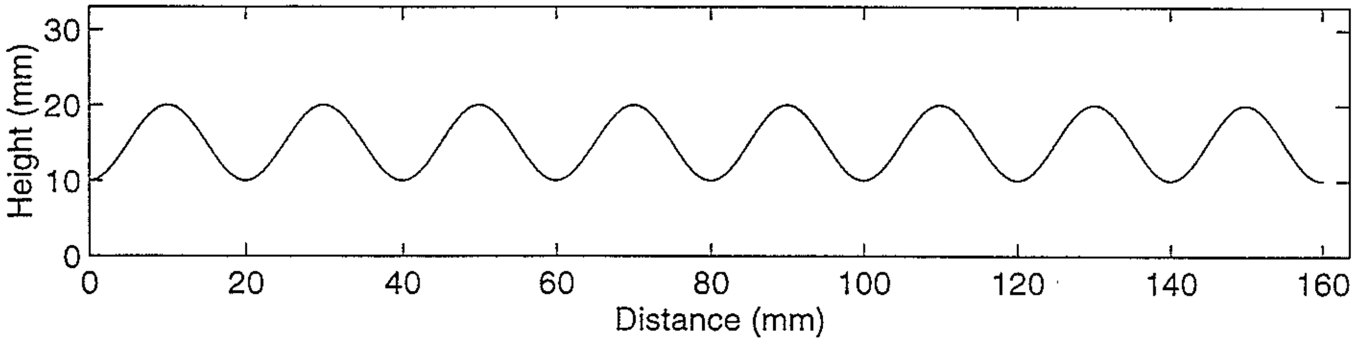
Data File: sinexx.dat p1/2
Analysed 3-Dec-96 15:14

WORKS CONSULTANCY SERVICES LTD, CENTRAL LABORATORIES, roadpro.m version 3-December-1996

Test Date : 3 Dec 96
Site·Identification :
Wheelpath :
Site Description : Theoretical sinewave profile
Comments :
Operator : Paul Carpenter

Test section length : 2000 mm Traverse speed : 99.99 mm/s
Traverse speed variation (%) : 0.004867 ok <1%
Sampled 1e+004 points @ 500 Hz
Maximum voltage : 6.115 Minimum voltage : 3.057 ok
Possible invalid data (%) : 0
Effect of overall slope has been removed from all height analysis.
Mean height : 15 mm Std dev height: 3.536 mm
Maximum height : 20 mm Minimum height: 10 mm

Section of measured profile - first 160mm



Pavement texture measurements

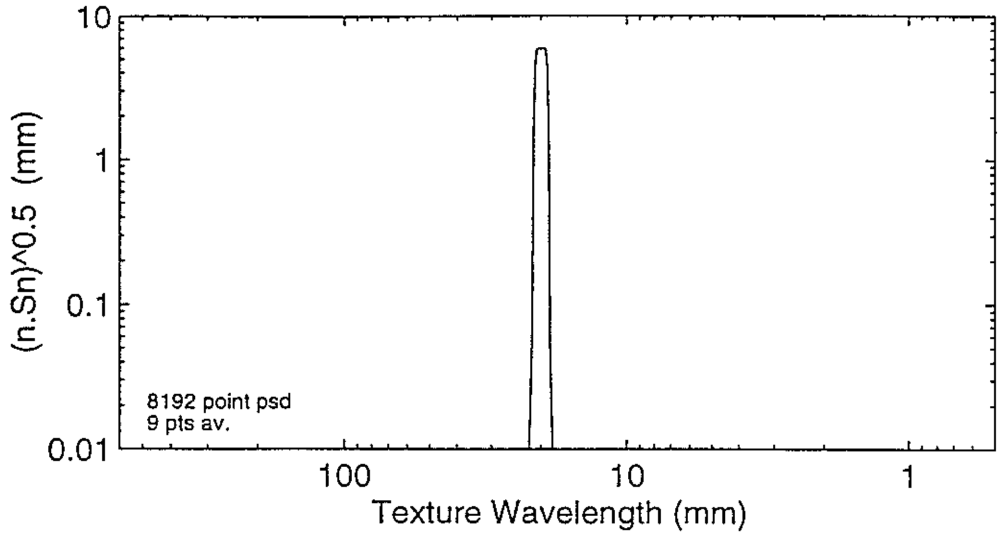
Lma :	70.97 dB(Ma)	(3.535 mm rms)	Lme :	-11.47 dB(Me)	(0.000267 mm rms)
L5mm :	-66.71 dB(5mm)	(4.621e-007 mm rms)	L80mm :	-44.61 dB(80mm)	(5.882e-006 mm rms)
Tdma :	7.931 mm		ERNL :	54.37 dB(A)	

Mean Profile Depth analysis to ISO Standard 13473-1

The following measurements based on the average of 20 segments of 100 mm.

MPD : 5.012 mm ETD : 4.21 mm RMS : 3.539 mm

Standard deviation of individual MPD values : 0.0000696 mm



Third-Octave Band Spectral Levels

Wavelengths and texture levels (dB relative to 0.001 mm std)

500 mm	-12.3 dB	50 mm	-45.6 dB	5 mm	-74.7 dB
400 mm	-20.3 dB	40 mm	-39 dB	4 mm	-80.6 dB
315 mm	-26.3 dB	31.5mm	-30.2 dB	3.15mm	-84.7 dB
250 mm	-29.7 dB	25 mm	-6.2 dB	2.5 mm	-88.8 dB
200 mm	-37 dB	20 mm	71 dB	2 mm	-79.2 dB
160 mm	-42.5 dB	16 mm	-8.7 dB	1.6 mm	-82.9 dB
125 mm	-45.7 dB	12.5mm	-35.8 dB	1.25mm	-79.7 dB
100 mm	-49.1 dB	10 mm	-49.6 dB	1 mm	-72.3 dB
80 mm	-50.3 dB	8 mm	-59.7 dB	0.8 mm	-83.2 dB
63 mm	-48.8 dB	6.3 mm	-67.7 dB	0.63mm	-81.6 dB