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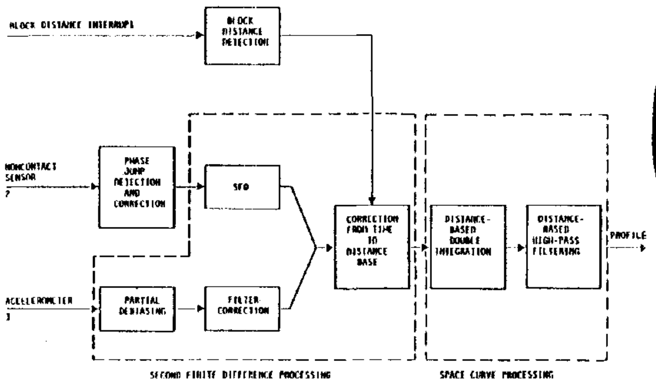
Report No. FHWA/RD-81/068

NONCONTACT ROAD PROFILING SYSTEM

Vol. 1. Overview and Operating Manual

October 1981
Final Report



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FOREWORD

This report is a summary of the work done under a contract for developing the data processing for a road profile measuring system using an inertial reference. The analog signals of an accelerometer and height sensor are A/D converted, sampled and processed. The time based signals are converted to a distance base, using a speedometer generated signal. The processing combines the accelerometer and height signal and produces a road profile independent of speed and direction of travel. The sampling parameters can be selected to provide desired wavelength cutoff between 0.5 and 300 feet. This range covers all the wavelengths of interest for pavement vehicle interactions, while removing the effect of grades.

This volume also includes instructions for system operation and is being distributed by FHWA memorandum to individual researchers.

Richard E. Hay/for
Charles F. Scheffey
Director, Office of Research
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NOTICE

ACKNOWLEDGMENTS

Many ENSCO employees made substantial contributions to this project, the role of the listed author being to pull together and organize the material, obtain the numerical results, and write the report. John Corbin was the original principal investigator; he developed the hybrid processing scheme and made an early diagnosis of the acoustic probe difficulties. Joe Zaiko designed and helped build the electronics. George Gunn did the original computer programming. Ed Howerter developed a preliminary design for an online processing system. Jeff Bloom designed the mechanical components. John Hinch, Bill Jordan and Meena Baluja collected and digitized the data.

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1.0 PROJECT OVERVIEW

1.1 INTRODUCTION

The following material states the project objectives and scope. It also describes the resulting system broadly but in sufficient detail to operate the system. A more detailed description and some results are provided in Part 3 - Project Report. This overview serves as an introduction to the project report.

1.2 THE ACOUSTIC PROBE SYSTEM

The long wavelength [1/2 to 300 feet (0.2 to 90m)] components of longitudinal highway profile affect vehicle dynamics, which in turn affect driver comfort and control as well as vehicle deterioration. These profiles can be measured using an instrument such as the General Motors road profilometer[1], which employs a small wheel rolling beneath a van to measure the distance between the van body and the pavement. Because of the wheel's inertia, these instruments are not accurate at high speed.

In order to avoid the limitations of wheel inertia, the Federal Highway Administration (FHWA) has developed a non-contact profile-measuring instrument.[2] This instrument uses an acoustic sine wave reflected from the pavement surface to measure the distance to the pavement, as shown in Figure 1. A reference wave provides partial compensation for variations in acoustic wavelength due to temperature changes. Bandpass filters improve the received signal-to-noise ratio, and a phase meter measures the phase between the two signals, which

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[1] E. B. Spangler and W. J. Kelly, "GMR Road Profilometer - a Method for Measuring Road Profile," Highway Research Record 121, Highway Research Board, 1966.

[2] R. P. Joyce, "Development of a Noncontact Profiling System," Report FHWA-RD-75-36, January 3, 1975.

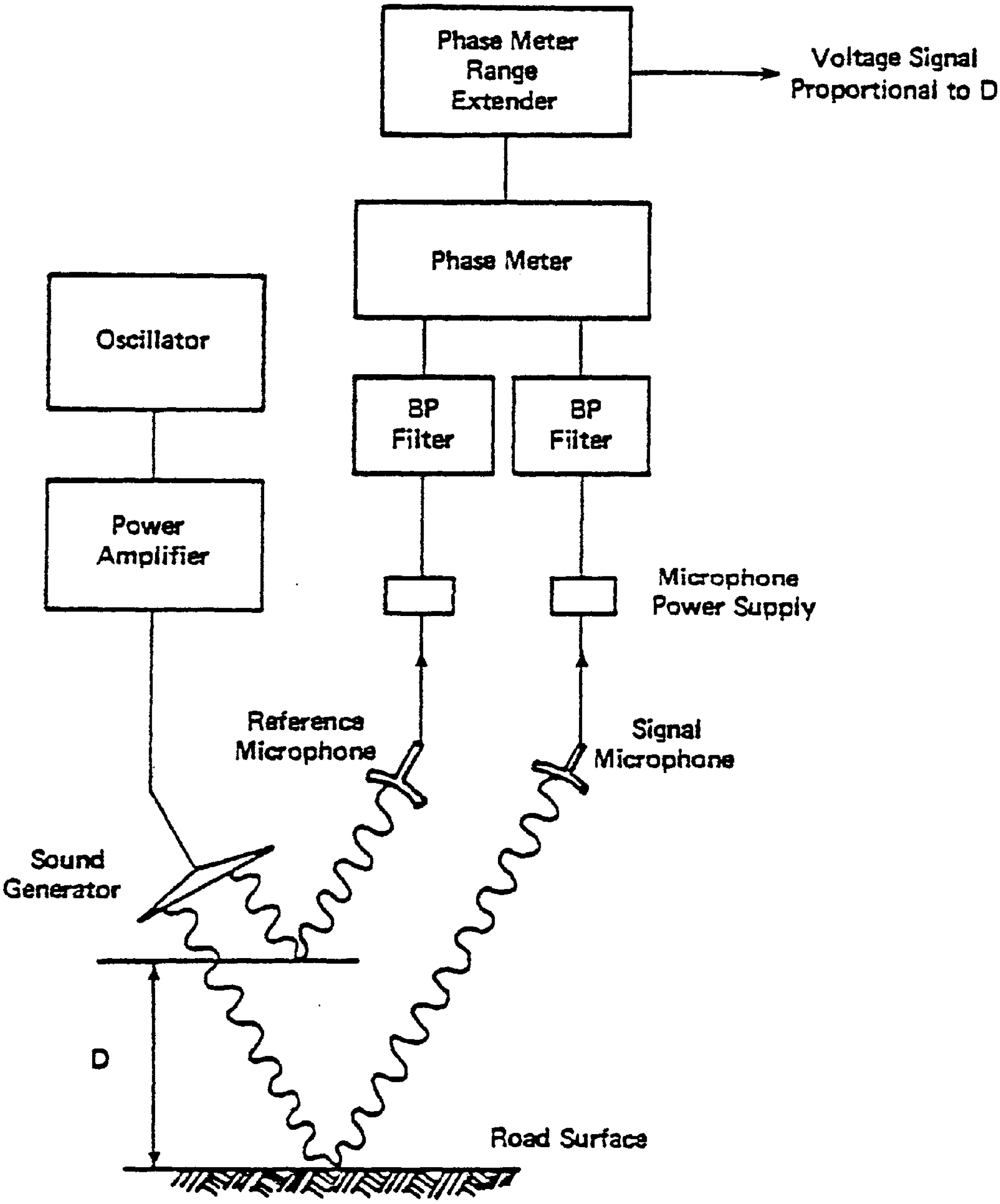

Figure 1. Schematic Diagram of the FHWA Noncontact Sensor

is directly proportional to variations in the path length.

The phase meter has a range of 360 degrees: when the phase goes beyond 360 degrees, the reading jumps back to zero and starts over. Similarly, when the phase becomes negative, the reading jumps to 360 degrees. The range extender's function is to detect these jumps and add or subtract the equivalent of 360 degrees so that the phase output is unambiguous over a range of several wavelengths.

This noncontact instrument, called an acoustic probe, measures pavement profile relative to the instrument. In order to obtain an absolute profile measurement, it is necessary to measure the instrument's trajectory. This is obtained from an accelerometer whose output is double integrated to provide displacement. The acoustic probe output is added to the double-integrated acceleration to provide the desired profile measurement.[3]

1.3 PROJECT OBJECTIVE

Although the concept of double integrating acceleration to obtain displacement is simple, the concept is difficult to carry out in practice. The basic difficulty is that any error in acceleration will grow without bound when double integrated. The error can be controlled by analog high-pass filtering, which effectively limits the integration interval, but such filtering distorts the output and sacrifices long wavelength information (such problems are discussed in the Wambold report).

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[3] See J. C. Wambold, "The Evaluation of a Noncontact Profiling System Using the Acoustic Probe," Report FHWA-RD-78-43, March 1978, (also published in Public Roads, December 1979, pp. 106-113).

There are also other problems with analog integration and filtering:

- they are causal, which means that a different profile will be indicated when traveling over a given pavement north-to-south as opposed to south-to north;
- they are time-based, which causes them to be speed dependent.

Consequently, different profiles will be measured for the same pavement if it is traversed at different speeds or in different directions.

The objective of this project is to produce a data processing system for a noncontact sensor that has the following desirable characteristics:

- recovers profile wavelengths of 1/2 to 300 feet (0.2 to 90M),
- has no phase distortion,
- provides filtering and output profile as a function of distance rather than time, and
- is independent of vehicle speed and direction.

1.4 PROCESSING APPROACHES

As just mentioned, analog processing has the inherent problems of causality, time dependence and phase distortion, all of which are severe limitations when processing highway profile data.

Digital processing using symmetric finite impulse response (FIR) filters can avoid the problems of causality and phase distortion. With digital processing it is possible to convert from a time to a distance base before filtering or integration and thus overcome the limitation of time (speed) dependence.

Accelerometer data, which characteristically has substantial high frequency content, poses a problem for digital processing. The high frequency portion is unnecessary for profile measurements, but it taxes the data recording and digitizing processes. Therefore, some preliminary analog filtering of the accelerometer data is mandatory.

The most satisfactory processing approach is a hybrid one in which some analog filtering is done to the accelerometer data, but the bulk of the processing is done digitally.

1.5 SUMMARY OF THE DATA PROCESSING TECHNIQUE

1.5.1 HARDWARE

Figure 2 illustrates the data processing sequence. There are three input measurements:

1. a longitudinal distance measurement taken from the vehicle's speedometer drive,
2. a vertical measurement from the pavement to the vehicle by means of the noncontact sensor, and
3. the vehicle's vertical acceleration.

A tachometer encoder operates from the speedometer drive to provide pulses equally spaced in distance. The digital control board counts these input pulses and produces an output block

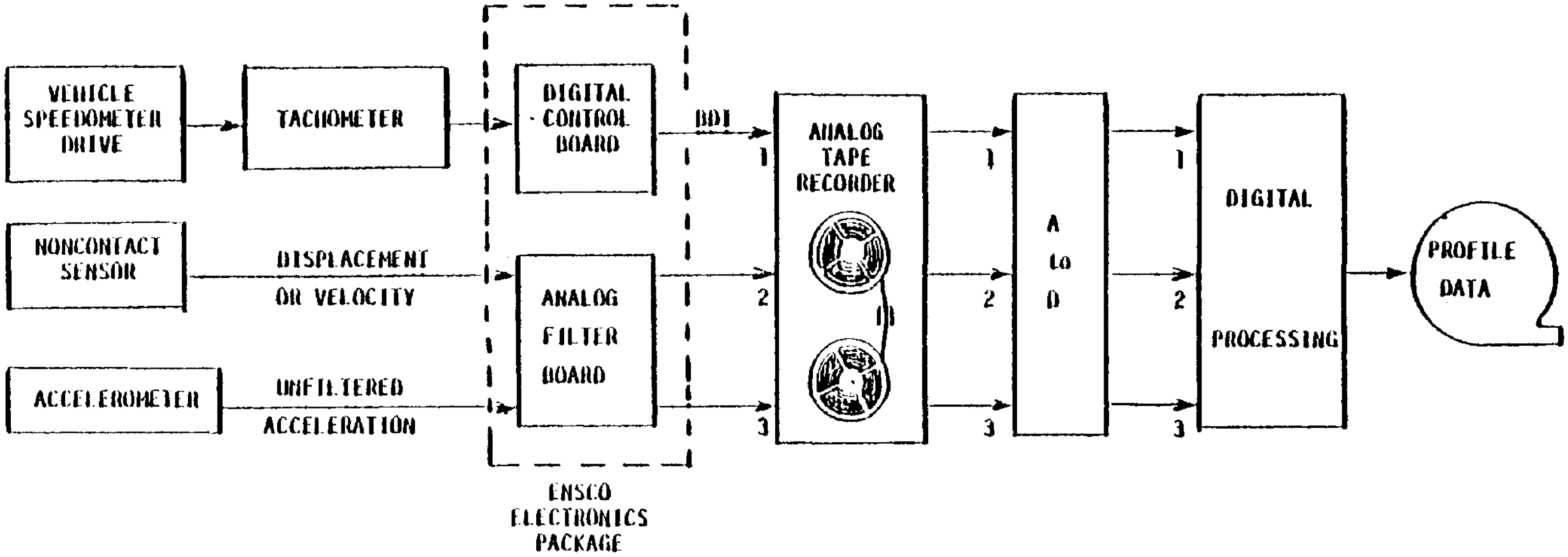

Figure 2. Block Diagram of the Data Processing

distance interrupt (BDI) pulse for each N input pulses. External block distance selection switches and internal calibration switches can be used to set N so that a BDI pulse is produced for each 1, 2, 4 or 8 inches (2.5, 5, 10 or 20 cm) of travel, as selected.

The current noncontact sensor is the acoustic probe. Any sensor that measures relative motion - whether by contact or not - can be used in place of the acoustic probe. All that is required is that the sensor's output voltage be proportional to either relative displacement or relative velocity. If a displacement sensor is used, the analog filter board applies an adjustable gain to the signal. If the input is velocity, the analog filter board also applies a single pole filter, $\omega_V/(s + \omega_V)$; although the analog filter board provides for this filter, actual filter component values will have to be calculated and the components will have to be installed if a velocity sensor is used.

Normally the acoustic probe signal would be taken from the phase meter range extender, as indicated in Figure 1. The range extender may not always detect phase jumps properly, however, so the current data processing system takes the output directly from the phase meter without using the range extender. The phase jump processing is then done downstream in the digital processing where more powerful techniques are available.

The accelerometer signal is passed through a double pole filter, $\omega_a^2/(s^2 + \omega_a s + \omega_a^2)$, which is also located on the analog filter board. This filter is used instead of the other acceleration filters available on the van.

The three channels of data, BDI, displacement/velocity and filtered acceleration, are stored on analog tape. Later these data are digitized and processed to create an output digital tape containing absolute pavement profile height as a function of distance.

The digital processing is now done offline, but the project included the preliminary design of an online (real time) data processing system. For online processing the analog tape recorder would be eliminated, and the BDI would be used to drive the digitizer at the selected distance interval. The profile output would be stored on tape and displayed on a stripchart recorder. The digital control and analog filter boards have been designed so that they would plug into the selected online minicomputer, a Texas Instruments model 990/10. It is anticipated that the online system would be developed as an extension of this project once the offline system has been demonstrated successfully.

A detailed description of the hardware is provided in Part 3, Volume 2, of this report.

1.5.2 SOFTWARE

In the hybrid approach, most of the data processing is done digitally. Below is a description of the operations performed in the digital processing block in Figure 2. This block is expanded in Figure 3, which is called a conceptual block diagram because the actual processing does not divide into the convenient blocks indicated in the diagram.

For acceleration input, a correction is made for the amplitude attenuation introduced by analog filtering of this channel. Most of the bias in the accelerometer signal is also removed in order to reduce the quadratic growth of error that occurs when the bias is double integrated.

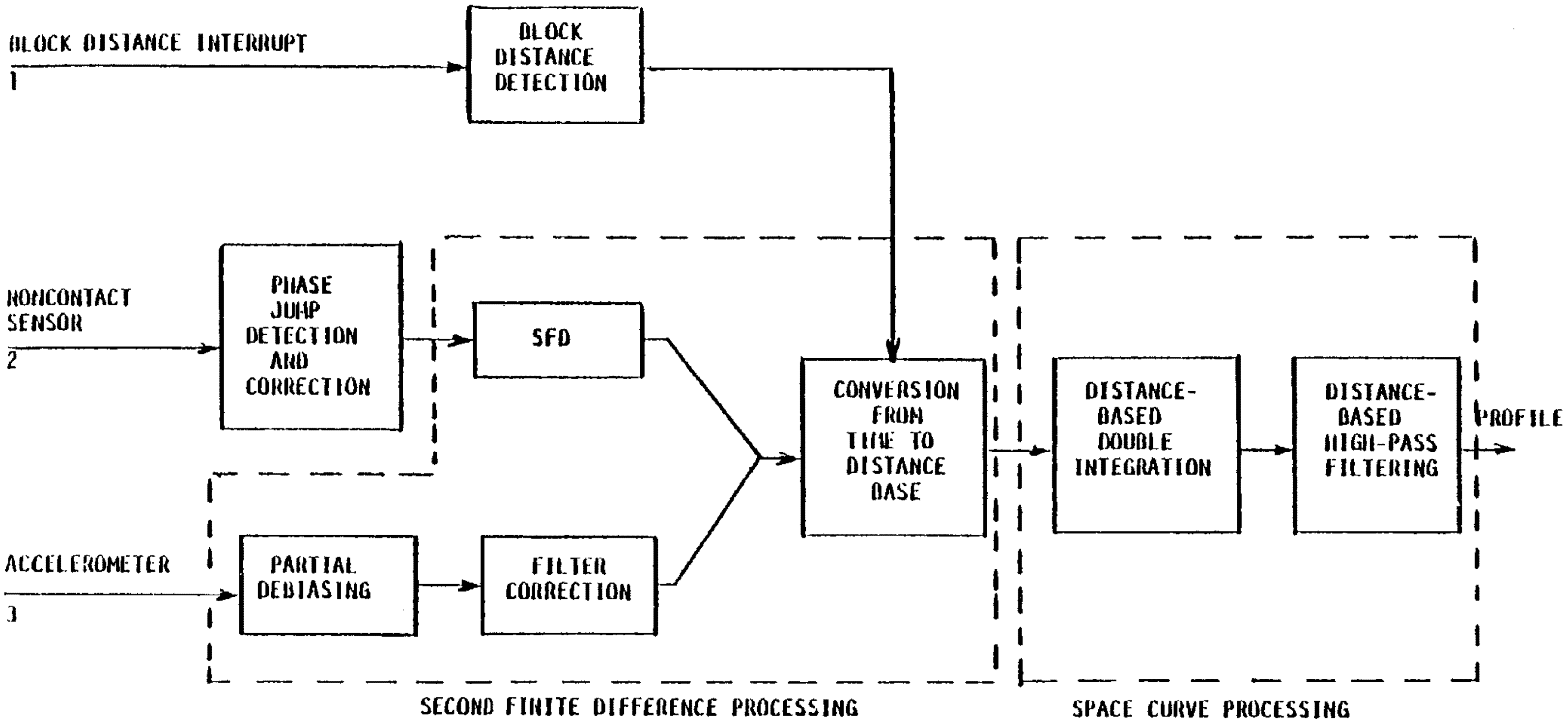

Figure 3. Conceptual Block Diagram of Digital Processing for Acoustic Probe Input (Displacement Input Mode)

For noncontact sensor input from the acoustic probe, the first step is to detect and correct for phase jumps (a digital substitute for the range extender). Then a time-based second finite difference (SFD) is calculated. For a noncontact displacement sensor other than the current acoustic probe, the phase jump calculations are not used. For velocity rather than displacement input, digital compensation is made for the analog velocity filter, and then a first finite difference is taken so as to obtain the common SFD medium. The SFD is chosen to be the medium for combining displacement, velocity and acceleration signals and for converting from a time to a distance base.

To establish the profile of the road surface, the vertical movement of the vehicle (as measured by the inertial accelerometer) must be added to the distance from the accelerometer to the road surface (as measured either by an acoustic probe or a velocity transducer). The outputs of the different transducers in the forms of acceleration, velocity or displacement must be converted to a common base at some point during the profile computation so that they can be combined. The SFD is chosen because it is the finest representation of the second derivative allowed by the sampling rate. It therefore contains all the information that is obtainable at the sampling rate. The frequency response of such a representation has no nulls occurring between the wavelengths of infinity and two times the sampling distance. This permits the mathematical reconstruction of the space curve of any wavelength longer than twice the sample distance, limited only by the resolution of the system and the noise contamination in the signals. The software developed for the system provides the input points for handling acceleration, velocity and displacement measurements.

The block distance interrupt is used to count the number of time sample intervals in each distance sample interval. This number is used to make the conversion from time to distance base.

Since the final calculated road profile is to be presented as a function of distance, conversion to a distance base is necessary. Due to the fact that most transducers, as well as filters used to condition output signals, have responses which are dependent on temporal frequency, their outputs will be affected by vehicle speed. Proper compensation is necessary in order to insure that distance-based profile measurements are independent of the speed of the measurement vehicle. These compensations are made during the conversion of the time-based SFD to the distance-based SFD. The block distance pulse is used to provide information on the speed of the vehicle to the software from which the compensations are made.

The so-called space curve processing is used to obtain the profile from its SFD. The first step is digital double integration. Then high-pass filtering is used to eliminate those components of the signals that would cause unbounded growth of the output. Because these operations are distance-based, the filter cutoff wavelength is a constant distance independent of the speed at which the data is collected, and because symmetric FIR filters are used, there is no phase distortion in the output signal.

A detailed description of the digital processing is provided in Volume 3 of this report.

2.0 SYSTEM OPERATION

2.1 INSTRUMENTATION SETUP

Instructions for operating the acoustic probe, the accelerometer and their associated electronics are provided in the reports by Joyce and Wambold cited previously. Below are described modifications in the procedure needed to operate the equipment in the hybrid processing mode developed under this project.

2.1.1 ACCELEROMETER FILTERING AND SENSITIVITY

The ENSCO Electronics Package (EEP) provides the only analog filtering that should be applied to the accelerometer signal. Therefore, the 10Hz low-pass filter provided in the Sundstrand Model 517 accelerometer amplifier should be switched out, and the 1.0 rad/sec RC high-pass filter intended for the output of the Sundstrand 517 should be bypassed (see the Wambold report, p. 42).

The accelerometer range should be set at 0.2g/volt, and the sensitivity should be set at 250 mu/g.

2.1.2 RANGE EXTENDER

The range extender is connected to the phase meter through a nine-pin plug P151 and jack J151 on the back of the phase meter (see Appendix B of the Joyce Report).

The phase meter provides an inverting switch on its front panel. The switch has a normal position and an "add 180 deg" position that inverts one of the input signals, effectively adding ±180 degrees to the reading. When the range extender is plugged in through P151/J151, the inverting switch is disabled and inversion is controlled by the range extender (inversion occurs whenever the phase reading falls below 45 degrees or rises above 315 degrees). The system is designed so that inversion reverts to its original switch-controlled mode when P151/J151 are disconnected.

Because automatic inversion (controlled by the range extender) corrupts the phase meter reading, it is essential that P151/J151 be disconnected when digital phase jump processing is used.

2.1.3 WIRING CONNECTIONS

The following connections are needed to operate the data processing system described here:

- Connect the power cord from Jack J8 on the EEP to a 115 volt, 60 Hz, source.
- Connect cable E1 from the tachometer encoder to jack J7 on the EEP.
- Connect a cable from jack J3 on the EEP to input no. 1 on the tape recorder (block distance channel).
- Connect a cable from the phase meter output, jack H7 on the bus panel, to jack J4 on the EEP.
- Connect a cable from jack J1 on the EEP to input no. 2 on the tape recorder (acoustic probe channel).
- Connect a cable from the accelerometer amplifier to jack J5 on the EEP.
- Connect a cable from jack J2 on the EEP to input no. 3 on the tape recorder (accelerometer channel).
- Connect a cable from tape recorder input no. 2 to stripchart channel no. 1 (optional phase meter display).

- Connect a cable from tape recorder input no. 3 to stripchart channel no. 2 (optional accelerometer display).

2.1.4 TAPE RECORDER

The tape recorder speed should be 7-1/2 inches/sec (5 kHz bandwidth) to capture the block distance pulses.

Table 1 gives suggested tape recorder voltage levels. The input accelerometer level may have to be changed from the suggested value depending on the vehicle speed and pavement roughness.

TABLE 1

TAPE RECORDER VOLTAGE LEVELS

CHANNEL	SIGNAL	INPUT	OUTPUT
1	Block Distance	5.0v	1.41v
2	Noncontact Sensor	1.41v	1.41v
3	Accelerometer	3.5v	1.41v

2.1.5 ENSCO ELECTRONIC PACKAGE (EEP)

Wiring connections to the EEP are covered in Section 2.1.3. Turn the power switch on, and turn the calibration switch to "normal."

The two block distance switches on the EEP determine the pavement profile wavelengths that can be recovered in the digital processing. The range of wavelength of interest is dictated by what is important to road vehicles. Profile variations induce pitch, bounce and roll modes of motion in vehicles, as well as oscillations in wheels and suspension systems. The lowest frequency of interest at the highest expected vehicle speed determines the longest wavelength of concern.

For instance, if the lowest resonant frequency in a vehicle is 0.8Hz and the highest speed is 55 mph, the longest wavelength of interest would be 100 ft. The shortest wavelength of interest, on the other hand, is related to the highest frequency of interest in the vehicle. However, the capability of the system at the high frequency end is limited by the sampling rate. Once the desired range of wavelengths has been determined, the material provided in Section 2.5.1 can be used to set the block distance switches properly. Four settings are available, 1, 2, 4 and 8 inches (2.5, 5, 10 and 20cm).

2.2 CALIBRATION

Calibration of the data processing system is covered in Part 2 of this report, which is bound separately.

2.3 DATA COLLECTION

Data may be collected at any speed from 10 to 60 mi/hr (16 to 97 km/hr), but error may be introduced at low speeds on non-level terrain by the accelerometer's inclination (see Part 3, Volume 1, of this report). If significant grade or cross slope variations exist, two measurements should be made, one at moderate speed and one at high speed. Any variation in the two resulting profiles is an indication of the error in the moderate speed run.

In order to correlate longitudinal position in the processed data with the pavement surface, a bump with a distinctive signature should occur in each run. The bump can either be natural (a manhole cover, for example) or artificial (a board placed on the surface before the run). A log should be kept of tape recorder footage for each run.

The block distance switch settings should be noted for future reference. This information is not required for the digital processing, but it is needed in order to determine the bandwidth of the digital output.

2.4 DIGITIZING THE DATA

The analog data should be digitized at 4000 scans/sec in order to capture the block distance pulses. Anti-alias filtering is recommended at 1500Hz for all three channels. For a 10 volt full scale, 12-bit digitizer, a digitizing gain of 5.0 is suggested for all channels.

The digitized data should be in the following form:

- one header record of 80 characters;
- data records with three channels by 256 scans (768 values) of data each; and
- twelve-bit data values placed in the twelve least significant bits of each location in the data record array.

2.5 DIGITAL PROCESSING

2.5.1 SPACE CURVE FILTERING

The digital processing includes a space curve filter that suppresses long wavelength components of the output profile. The filtering is done for two reasons. One is that it effectively limits the integration interval and thus controls the unbounded output that would otherwise be created by double integrating accelerometer bias and noise. The other reason is that for long wavelengths on the order of 1000 feet (300m), large amplitude terrain variations would overwhelm the small amplitude roughness variations of interest. Therefore, it is important to select the filter cutoff wavelength so as to obtain the desired roughness wavelengths without including terrain variations or integration error.

As explained in detail in Volume 3 of this report, the cutoff wavelength ($1/\sqrt{2}$ amplitude) is

$$\lambda_c = 1.843\ D\ (2^n - 1)$$

where D is the block distance interval selected on the EEP when the data are collected and n is the filter exponent selected when the digital processing is done.

Integer n has four possible values, 5, 6, 7 or 8. Table 2 gives the available cutoff wavelengths obtained from the above formula.

TABLE 2

SPACE CURVE CUTOFF WAVELENGTHS

(in feet, 1 foot = 0.305m)

	n, Exponent in the filter			
Sampling Interval D	n=5	n=6	n=7	n=8
1 inch (2.5 cm)	4.8	9.7	19.5	39.1
2 inches (5 cm)	9.5	19.3	39.0	78.2
4 inches (10 cm)	19.0	38.7	78.0	157
8 inches (20 cm)	38.1	77.4	156	313

For digital data there is also a minimum wavelength that can be recovered according to the sampling theorem:

$\gamma_0 = 2D$, where D is the sampling distance interval and γ_0 is the short wavelength cutoff.

Table 2 indicates that similar cutoff wavelengths can often be obtained with different combinations of n and D. For example, n = 6, D = 1 inch (2.5cm) gives a result similar to n = 5, D = 2 inches (5cm). Observe, however, that the large n, small D combination gives a broader spectrum because λ_0 is smaller for smaller D. On the other hand, the large n, small D combination has the potential for greater error (see Section 2.5.4)

(Although D is normally considered fixed once the data are collected, it is possible with offline processing to collect all data at D = 1 inch (2.5cm) and then modify the software so that the block distance pulses can be deleted or passed over as desired. For example, if three out of four pulses are suppressed, then data with D = 4 inches (10cm) results. In this way various combinations of n and D can be tried to obtain the best results. This approach is illustrated in Volume 3, Section 7.6, of this report.

2.5.2 PROGRAM INPUT

The input is of two types, the digitized data to be processed, which are read from unit 9;* and the run parameters, which are read from unit 5.*

Data to be Processed

The data to be processed (unit 9) are in the form of a header record and data records of 256 scans each, as described in Section 2.4. The variables supplied for each scan are (1) block distance, (2) noncontact sensor, and (3) accelerometer. These data are normally supplied from a magnetic tape that is the output of digitizing.

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*Unit numbers are input device designations, their number assignment depend on the configuration of the computer system used.

Run Parameters

The run parameters (unit 5) comprise eight values:

- MIN, the first data record to process;
- MAX, the last data record to process;
- FREQ, the digitization frequency in scans/sec:
- NFIL, the space curve filter exponent, n, discussed in Section 2.5.1;
- MODE, the noncontact sensor mode flag, which may be 0 for a displacement sensor or 1 for a velocity sensor;
- SCALE, the scale factor ratio, which is described below;
- OMEGAA, the acceleration filter corner frequency, ω_a, in radians/sec; and
- OMEGAV, the velocity filter corner frequency, ω_v, in radians/sec.

The scale factor ratio is the ratio of two values. The first (numerator) is the acceleration value of one count of the integer acceleration input data. Its units are distance/sec^2 per count. The second value (denominator) is the displacement or velocity value of one count of the noncontact sensor data. It has units of distance per count or distance/sec per count, respectively. The scale factor ratio thus has units of sec^{-2} or sec^{-1}, respectively.

The scale factor ratio may be calculated initially from the sensitivities and gains in the acceleration and noncontact sensor channels. These will yield the two appropriate values per count, which are then divided to yield the ratio. The ratio may be determined more accurately by using the vertical acceleration calibration procedure described in Volume 2 of this report.

The input filter corner frequencies must match the values built into the EEP, except that any value, for example 0., can be used for OMEGAV if in the displacement mode (MODE = 0). The value of OMEGAA used in the EEP is 61. rad/sec.

The eight run parameters values are input on two card images. The first card image gives MIN and MAX in 2I10 format. The second card image gives FREQ, NFIL, MODE, SCALE, OMEGAA and OMEGAV in F10.0, 2I10, 3F10.0 format.

The following input is an example:

```
column   1         2         3         4         5         6
         0         0         0         0         0         0

      1201      1700
     4000.         8         0      466.       61.        0.
```

The card images may be actual cards or images entered from a terminal or disk file, depending on how unit 5 is assigned.

2.5.3 PROGRAM OUTPUT

As in the case of the input, the output from the digital processing is of two types, the processed digital data, which are written on unit 10, and a listing of the run parameters, which are written on unit 6.

Processed Data

The processed data file (unit 10) comprises a header record of 80 characters (the same header read from unit 9), followed by the output data records. Each data record contains 256 scans with five integer variables per scan. The variables provided are, in order,

- the raw noncontact sensor signal,
- the noncontact sensor signal after phase jump processing,
- the raw accelerometer signal,
- the distance-based SFD (see Figure 3) and,
- the computed highway profile.

The digital processing does not scale the input noncontact sensor data. Therefore, if the displacement input mode is used, all of the output except the acceleration will have the same scaling in distance per count as the input noncontact sensor data.

Because the input data is time based and the output is distance based, and because delays are introduced in the processing, there is not a simple relation between input and output record numbers. For example, the results corresponding to input record N will not be found in output record N.

The processed data is normally in the form of a tape, which is suitable for plotting, listing, or input to another processing program. The output may also be placed on a disk file or other convenient device.

Run Parameters

The run parameters and input header record are written on unit 6* This provides a permanent record of the digital processing.

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*Unit 6 is an output device, the exact number designation will depend on the configuration of the computer system used.

2.5.4. POTENTIAL DIFFICULTIES IN DIGITAL PROCESSING

As discussed in Section 1.3, double integration is difficult to perform in practice. The digital processing has been developed and tested with the objective of minimizing accelerometer bias and minimizing the effect of any remaining accelerometer bias or noise. The user should be aware of the potential difficulties and their solutions, however, in order to use the digital processing software effectively. Some of the most commonly experienced difficulties are related to the quality of the acceleration signal. A large or a drifting transducer bias can cause the processor to diverge. A slight noise contamination to the acceleration measurement, such as the onset of bearing noise and larger than specified hysteresis, can produce large errors in the processed profile output. Changes in transducer amplitude or frequency response (such as a similar but different accelerometer).will invalidate the built-in software compensation and produce erroneous results.

The Difficulties

The space curve processing calculates the bias in the signal and removes it so that the output signal should be free of bias. If bias is observed in the output, then this operation is not functioning properly, probably because the data being processed requires greater numerical precision than is available in the algorithm. Several solutions to this problem are discussed in the solutions section below.

Overflow is also a possibility in the debiasing operations. It would be indicated by error messages or by erratic results after a certain point in the output.

The block distance and phase jump calculations both involve the detection of certain signatures in the data. If the gains in the hardware are changed, these signatures will change, and it may be necessary to adjust the corresponding constants in the computer program in order to obtain proper detection. Procedures for adjusting the constants are given in Volume 2 of this report.

The Solutions

The accelerometer bias is calculated by averaging the accelerometer signal over the first IBIAS time-based scans. Currently IBIAS = 10,000, so that averaging is done over the first 2.5 seconds of data processed. If accelerations below 1/2.5 = 0.4Hz are significant then the value of IBIAS should be increased. If operating conditions, such as highway grade and cross slope, change during a run, then it may be necessary to restart the digital processing occasionally so that a reasonably current value of accelerometer bias is used.

In addition to the accelerometer bias, quantities D (the distance sample interval) and NFIL (the filter exponent) affect the precision of the space curve calculations. Large values of D are preferable from the standpoint of precision because the magnitude of the desired part of the SFD is proportional to D^2, whereas the undesired part (bias and noise) is constant. Therefore, the signal-to-noise ratio improves for larger values of D (this is illustrated in Volume 3, Section 7.6.2, of this report).

Larger values of NFIL require greater precision because a larger range of values is encountered in the calculations.

Observe that the small D, large NFIL combination, which gives the broadest spectrum (see Section 2.5.1), involves potentially troublesome values of both D and NFIL. Testing has shown that the computer program is normally capable of handling the smallest

D [1 inch (2.5cm)] available in conjunction with the largest NFIL (8) available without difficulty, but if difficulties arise in such cases, it will be necessary to make a compromise between accuracy and desired spectrum.

Some of the quantities in the computer program may grow without bound as the processing continues. If difficulty is experienced in processing very long runs, break the run into pieces and process them separately (this is the function of the MIN and MAX parameters in the input).

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16. Abstract

Road profiles are of interest because they affect vehicle ride quality, the wavelengths of concern ranging from 1/2 to 300 feet (0.2 to 90 m). This report pertains to a class of profile-measuring instruments in which an accelerometer measures vertical vehicle motion and a "noncontact" sensor measures vertical pavement motion - either displacement or velocity - relative to the vehicle. Specifically, a method is developed to process the accelerometer and noncontact sensor signals so as to obtain a measured profile with the following desirable qualities: (a) 1/2 to 300 foot wavelengths are recovered, (b) there is no phase distortion, (c) filtering and output are functions of distance rather than time, and (d) the output is independent of data collection speed and direction. A hybrid processing technique involving a minimal amount of analog processing is used. The digital processing, which is now done offline, makes use of symmetric finite impulse response filters. The processing algorithms are described in detail, and a variety of results are presented. The report is in four separately-bound units:

Volume 1 - Overview and Operating Manual - FHWA/RD-81/068
Volume 2 - Calibration and Maintenance Manual - FHWA/RD-81/069*
Volume 3 - System Software - FHWA/RD-81/070
Volume 4 - System Hardware - FHWA/RD-81/071*
* Available from NTIS only.

17. Key Words
Road roughness, profile measurement, hybrid processing, road profiles, digital double integration

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METRIC CONVERSION FACTORS

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km

AREA

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.6	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha

MASS (weight)

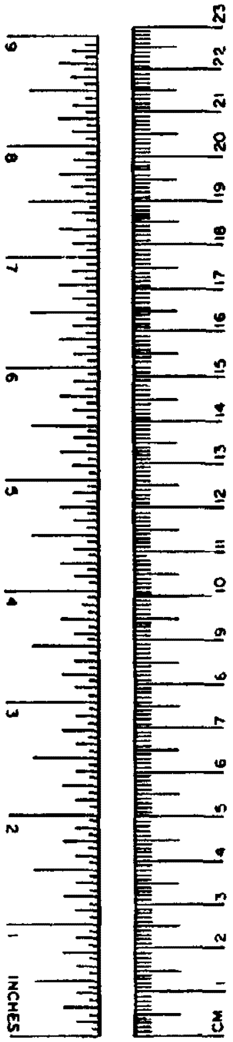
SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons(2000 lb)	0.9	tonnes	t

VOLUME

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³

TEMPERATURE (exact)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS FROM METRIC MEASURES

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1 1	yards	yd
km	kilometers	0.6	miles	mi

AREA

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares(10,000m²)	2.5	acres	

MASS (weight)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000kg)	1.1	short tons	

VOLUME

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ml	milliliters	8.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	36	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³

TEMPERATURE (exact)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F