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PROFILOMETER FOR BOMB-DAMAGE-REPAIRED AIRFIELD PAVEMENTS AND MEASUREMENT OF PAVEMENT UPHEAVAL; REPORT I: TECHNOLOGY EVALUATION

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Existing profilometers, each developed for highway applications, have limitations in respect to profiling bomb-damage-repaired airfield pavements. The components of existing profilometer systems are discussed in relation to the general requirements of a profilometer for bomb damage-repaired pavements, as are each of the profilometers themselves. The conclusions drawn concerning the use of existing profilometer systems for bomb-damaged airfield pavements are that they process profile data to provide information appropriate to highway operations; they do not function effectively at slow speeds, which may be necessary on an extensively damaged runway; and the costs prohibit supplying a unit to each station which may require expedient repair.

Crater upheaval is the disturbance about the crater itself, which may not be detectable by the human eye. The string line method, presently used by the Air Force to detect crater upheaval, is difficult to perform and sometimes unreliable. Other possible methods are introduced and should be integrated into a test plan to determine the worthiness of each for crater upheaval detection.

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PREFACE

This investigation was performed by the Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES), between April 1985 and March 1986. The study was sponsored by the US Air Force Engineering Services Center (AFESC), Tyndall Air Force Base, Florida, under Military Interdepartmental Purchase Request N 85-70 entitled "Profilometer for Bomb-Damage-Repaired Airfield Pavements." AFESC project officers were Major Robert R. Costigan and Capt Isaac J. Schantz.

The study was conducted under the general supervision of Dr. W. F. Marcuson III, Chief, GL; Mr. H. H. Ulery, Jr., Chief, Pavement Systems Division (PSD), GL; Mr. J. W. Hall, Jr., Chief, Engineering Investigations, Testing and Validation Group, GL; and Mr. R. W. Grau, Chief, Prototype Testing and Evaluation Unit. Personnel of the PSD who took part in the study were Mr. R. A. Bentsen; and Dr. A. F. Stock, who was under contract at the time of the study. This report was written by Mr. R. A. Bentsen and Dr. A. F. Stock.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.
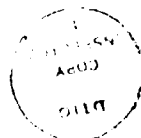
This technical report has been reviewed and is approved for publication.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	2.54	centimeters
miles (US statute)	1.609347	kilometers
pounds (force)	4.448222	newtons
pounds (mass)	0.4535924	kilograms

SECTION I

INTRODUCTION

A. OBJECTIVE

The United States Air Force (USAF) is currently developing rapid methods and procedures for repairing bomb-damaged airfield pavements. Sortie generation rate after an attack is critically dependent on quickly evaluating the launch surface before repairs start and after repairs are completed. Current technology may provide a method to make this evaluation quicker without losing the precision which is currently standard with the rod and level surveys completed by construction crews. This report covers the literature search and documents the state of the art for such devices.

B. BACKGROUND

The primary function of a pavement is to provide an acceptable level of service. One of the first indications that a pavement is not fulfilling this function is an increase in the volume of complaints concerning the quality of the ride over the surface. While complaints are essentially subjective, they are a response to the lack of a "smooth" surface profile that can be detected by measurement.

The importance of surface roughness in pavement studies was recognized many years ago, instrumentation for its measurement being described as far back as 1926 (Reference 1).

The American Association of State Highway Officials (AASHO) road test provided further evidence of the importance of surface roughness since it indicated that the present serviceability index (PSI) of a pavement can effectively be predicted by a measure of roughness alone (Reference 2). The PSI equations do include other parameters but their contribution is small.

The USAF has also recognized the importance of profile in relation to the safe operation of aircraft, developing a sophisticated simulation of the response of many of their aircraft to irregularities in the pavement surface during landing, takeoff, and taxi operations. The simulation is capable of calculating acceleration at various points in the aircraft and loads in the struts which carry the undercarriage. This simulation is very important in determining safe operating limits for aircraft over pavements with a known profile.

Many devices have been developed for measuring pavement profile. A report prepared for the Federal Highway Administration (FHWA) in 1973 reviewed the state of the art with respect to roughness measurement for highways (Reference 3). This FHWA report identifies several devices which have been developed to measure roughness but makes no recommendations for adoption.

C. SCOPE

The importance of the surface profile with respect to user perception and vehicle safety has been recognized for many years, but technological advance in relation to its measurement has been relatively slow. The earlier devices, which will be discussed later in this report, have tended to be either slow to use or very expensive to purchase. In addition, most of the work which has been reported has been directed toward developing a single parameter for a predefined section of highway pavement, facilitating decisions with respect to maintenance activities. This type of work is of limited value to the Air Force since its approach has been to simulate the response of an aircraft to a known profile. However, in recent years there have been some significant technological developments, particularly with respect to displacement measurements and noncontact type transducers. It is, therefore, timely to review the developments in technology to determine the applicability to current requirements of the US Air Force.

SECTION II

US AIR FORCE REQUIREMENTS FOR MEASUREMENT OF PROFILE
AND DETERMINATION OF UPHEAVAL

The system used by the Air Force to decide if it is safe to operate aircraft from any specific runway includes a computer simulation of the response of the chosen aircraft to the surface profile (Reference 4). The simulation checks for several potentially critical parameters, such as acceleration of the pilot's seat and loading in the landing gear. This simulation requires three longitudinal profiles, one for the nose gear and one each for the symmetrically placed main gear. While the aircraft is symmetrical about its center line, the surface is almost certainly not; therefore, it is necessary to measure all three longitudinal profiles. These three profiles must also be synchronized so that they give an accurate picture of the cross profile as well as the longitudinal profile, because the loading on the aircraft is influenced by the cross profile, and the computer simulation is able to model these effects. If the profile is synchronized, a precise representation of the surface, referred to a surveyor's datum, is not necessary. As long as the point-to-point representation of the profile does not omit frequencies essential to the simulation, an overall error of as large as 1 foot in each 100 feet* longitudinal distance (i.e., a rotation of the profile) will be unlikely to affect the result of the simulation of the aircraft operation.

At this stage of the project, it is not possible to make any statement about measurement precision. However, studies now in progress will provide information with respect to the significance of point-to-point errors of predetermined magnitude on the response of an aircraft. These studies are anticipated to provide insight into the precision requirements.

In addition to requirements related simply to the profile measurement, certain factors regarding operational environments must be considered.

The first operational requirement is to evaluate the repair of a bomb-damaged airfield and to periodically reevaluate this repair so that maintenance can be performed as necessary. This requirement includes the possibility of profile measurements being made under fire by personnel not trained in the operation of a profilometer. When considering this particular requirement, the Air Force needs a low-cost device stationed at each base that may be subject to hostile action. Speed of operation and robust construction are, therefore, significant factors.

The second operational requirement is to assure the quality of the new construction and to provide routine maintenance of the pavement during peacetime operations.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page v.

All ese requirements can conceivably be   t by one device.   However, the operating conditions pertaining to the second requirement are mu   re favorable because it is reasonable to expect a fully trained team   operators to be available. The equipment could also be operated at optimal speed for precision measurement, so that greater accuracy could be expected under these conditions. A further consideration is that the Air Force would not necessarily need to station one of these devices at each of its bases since profile measurement for routine maintenance would be a planned operation. A program including transport time is more realistic for this application.

An additional operating requirement regards the load on the pavement as the profile is being measured. Some crater-repair systems utilize special mats or planks to form the running surface. These mats may span voids or rest on high spots on the surface and therefore change form as an aircraft travels over the surface. For the purposes of this project, the Air Force has defined* a loaded profile as one that is measured as a device weighing 26,000 pounds or more travels over the surface and an unloaded profile is one that is measured under a load of 1,000 to 2,000 pounds.

While it is not possible to write a detailed specification at this stage of concept development, some significant requirements of the device can be identified.

> It must measure the point-to-point variation in a base profile rapidly and accurately.

> It must have a distance-measuring system that makes it possible to synchronize the three longitudinal profiles.

> It should be as compact as possible and non-vehicle-specific. If a device is to be available at each airbase, having a specific vehicle causes a substantial increase in cost and add limitations to the availability. Thus, a trailered ased device that can be towed by any vehicle available, including earth-moving equipment, is probably desirable.

In addition to the measurement of the pavement profile after repairs, the Air Force must measure pavements before repairs to determine the extent of restoration required. Bomb damage on airfield pavements includes surface craters and the disturbance of the pavement near the craters. The craters themselves are easily identifiable, but the disturbance, or upheaval, around them is not. The upheaval is caused by the disturbance of the base, subbase, and subgrade below the pavement surface due to a subsurface explosion, but the surface course of the pavement often remains undamaged. Accurately identifying the pavement upheaval is crucial in restoring the pavement to a condition that is usable by aircraft, because the upheaval ramps up to the repair and has an adverse affect on t   aircraft and the repair.

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* AFESC (RDC) M. J Costrouan, Letter, Subject: Ne ssit Measure for Profilometer nly for Bomb-Damaged Airfields (JON 262140),   3 Jun 87.

The current method of measurement used by the Air Force, called the string-line method, produces widely varied results when operated during adverse circumstances such as a rapid-repair situation. This report will discuss (a) the technology of measuring profile and the existing systems w' may have applications toward profiling bomb-damage-repaired airfield pavements, and (b) the present Air Force methods of detecting pavement upheaval and other methods that might prove to be more accurate and reliat .

PROFILE MEASUREMENT

Figure 1 shows a hypothetical profile with insets highlighting various features that may be encountered and that are of significance with respect to profile measurement.

First, the "actual surface" plot represents an accurate long-distance survey of the runway. Runway profiles are usually discussed in terms of wavelengths, and this type of plot can provide information on wavelengths up to infinity (i.e., that of a straight line). Burk and Clark (Reference 5) have reported a study to assess the effect of omitting undulations of various wavelengths from the simulation of aircraft response. This work is somewhat inconclusive in defining an upper limit for the wavelengths of roughness that affect the response of aircraft. As a result, Womack and Sonnenburg (Reference 6) state that all wavelengths above 400 feet can be omitted without affecting aircraft response. Hence, it can be concluded that the type of data available from a long-distance survey of the surface is not critical to an assessment of the effects of surface roughness on aircraft operations.

Small-scale profile typical of that found on both asphalt and concrete surfaces is also shown in Figure 1. An asphalt surface often contains pieces of mineral aggregate as large as 1 inch in nominal size placed closely together. A concrete surface may contain grooves cut transversely across the runway, spaced either at random or even spacing. The purpose of the small-scale profile is to ensure adequate skid resistance for the surface. Considering the operation of aircraft, this small-scale, short-wavelength surface profile is converted to noise and imparts negligible acceleration to the aircraft. However, it is not reasonable to assume that the profilometer does not need to measure short wavelengths. A step in the profile, also illustrated in Figure 1, is also a short-wavelength profile. This step could occur at faulting between two adjoining concrete slabs, as a small pothole, or even as an imperfection in some preformed surfacing component. With a 2-foot sampling interval, as used for current TAXI code simulations,* the step in the surface would appear as a ramp with a slope of 1 inch in 12 inches (assuming the surface on both sides of the step is horizontal) and would have a wavelength of 4 feet, which does not accurately represent the point-to-point change in surface profile. This raises a question concerning collection of data on short-wavelength roughness, which can be resolved without great difficulty as follows.

A small sampling interval (perhaps as small as a 1-inch spacing) will ensure accurate representation of features such as step functions. The use of a spatial transducer that has a footprint larger than the unwanted deviation on the surface will eliminate the inherently small features. The

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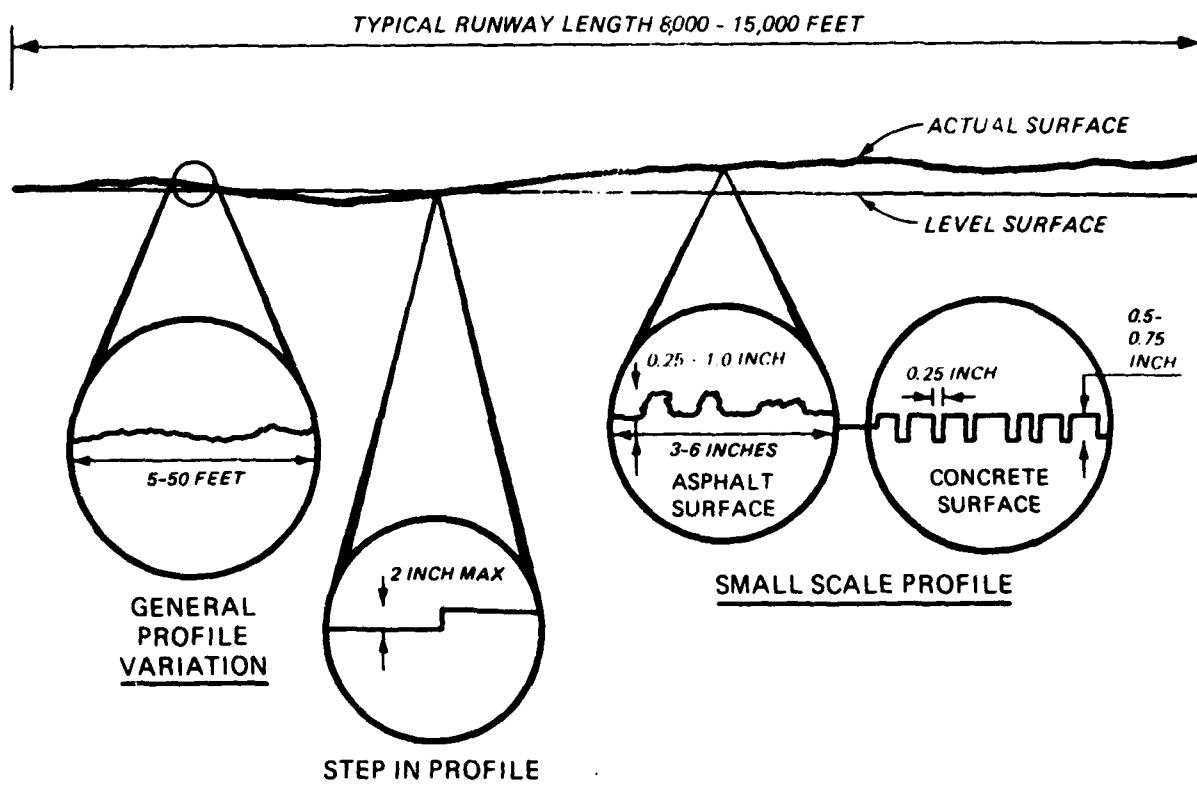
Figure 1. Pavement Surface Profile.

footprint size for displacement transducers will be discussed in the next section, but it is appropriate to discuss sampling interval here.

Although TAXI simulations are currently performed at 2-foot intervals, the program is capable of accepting data at more closely spaced intervals. However, it appears that no studies have been performed to evaluate the effect of adjusting the sampling interval to shorten the minimum wavelength from the 4 feet imposed by the usual 2-foot profile data spacing. It is possible that the compliance characteristics of the various aircraft tire and suspension system will effectively smooth a step function. It appears this is currently an unresearched phenomenon, so recommendations will be made for a study of this phenomenon.

A final factor to be considered is the processing of data. If a profile is required in real time, i.e., a presentation of the profile is made as the vehicle travels along the pavement, it is necessary to provide the system with the capacity to measure, record, store, and process the data at a rate compatible with the speed at which the system is traveling. Each data point will include longitudinal distance from the starting point, vehicle speed (which may be needed to correct for vertical motion of the profilometer), and vertical distance (which may itself be calculated). If data are required at relatively close intervals and high speeds, e.g. 3 inches at 55 mph, a real-time profile will probably require a high-speed computer. However, if the requirement is to record data for subsequent processing, the system requirements are less arduous.

COMPONENTS OF PROFILE MEASURING SYSTEMS

Profilometers are usually mounted on a wheeled vehicle that may be conventional transportation (automobile, van, etc.) or a specially constructed wheeled frame. The surface profile is usually derived from a measurement of the distance between the vehicle and the surface. This distance has to be corrected for the vertical movement of the vehicle itself, resulting from traveling over a rough surface. Therefore, profilometers generally incorporate a distance-measuring device and a further device and/or system for correcting for the motion of the vehicle.

The profile-measuring systems that have been constructed use a limited range of measuring devices. The most popular devices are accelerometers and displacement transducers. The displacement transducers can be subdivided into two categories--those which contact the surface and those which do not (noncontact transducers). This latter category can be subdivided into ultrasonic, laser, and infrared devices. The strengths and weaknesses of these individual devices are discussed.

A. ACCELEROMETERS FOR PROFILE MEASUREMENT

As the vehicle transporting the profilometer moves over the pavement surface, a record is obtained from which the profile can be determined. Any vehicle containing a profilometer must be equipped with some type of suspension, otherwise it will lose contact with the surface which could cause erroneous measurements. However, the existence of a suspension on the vehicle means that the measuring device will not follow the surface profile exactly. Accelerometers are incorporated into profilometers to produce data on the movement of the vehicle and to permit for corrections.

To convert the accelerations measured in the vehicle to displacement, it is necessary to double-integrate the accelerometer signal. This process introduces error to the system. All electronic measuring systems produce noise, the magnitude of which generally depends on the quality of the transducers and amplification system. If the acceleration of the vehicle carrying the profilometer is small, as it would be if the vehicle were moving very slowly, then the largest component in the output from the accelerometer could be the noise. Upon double integration, the noise component would be larger than the actual acceleration and, therefore, could introduce significant spurious data into the final stage of the displacement calculation. However, when the accelerations are more significant, e.g., when the vehicle is moving relatively rapidly, the noise is small in comparison with the signal from the acceleration, so the error introduced through integration of the noise becomes insignificant. It is, therefore, apparent that accelerometers are not suitable for use in profilometers intended to operate at very low speeds. The minimum practical speed for measurement can be determined, if data are available on the signal/noise ratio, for a given transducer, although, the magnitude of the signal depends upon the roughness of the pavement surface and the characteristics of the vehicle. Spangler,

Strong, and Brown (Reference 7) made an error analysis for a particular transducer, and their report may be used as a model for the assessment of accelerometers for profile measurement at various vehicle speeds.

Further errors can be introduced as a result of tilting the accelerometer. For reasons of economy and system simplicity, a unidirectional accelerometer is usually used for profilometers. The accelerometer is usually mounted so that its axis is perpendicular to the plane defined by the vehicle, which is generally parallel to the surface at that location. However, vehicles in motion over a surface are subject to pitching and rolling motions which will effectively tilt the accelerometer. In the tilted position, the accelerometer does not measure the vertical motion of the vehicle and so an error is introduced into the measurement of height. The significance of this error will depend upon the magnitude of the pitch-and-roll motion. If necessary, a three-dimensional (3-D) accelerometer can be used and the true vertical acceleration deduced from the measurements in three directions. However, this will significantly increase the volume of calculation required for profile measurement, and for real-time profile measurement will require faster processing facilities.

An alternative to the use of 3-D accelerometers has been suggested by Huft (Reference 8). In describing the profilometer developed for the South Dakota Department of Transportation (DOT), he stated that the error induced by accelerometer tilt appears as low-frequency accelerations that can be removed by appropriate low-pass filtering. This is a simpler and less costly solution than incorporating a 3-D accelerometer, but its practical value would depend upon the effect that the filtering has on the simulation of the response of the aircraft to the profile over which it is traveling.

B. DISPLACEMENT TRANSDUCERS FOR PROFILE MEASUREMENT

1. Surface Contacting Transducers

The General Motors road profilometer, which is probably the most widely publicized profilometer, used a surface-contacting transducer. This device and its use have been described in numerous publications (References 7, 9, 10, 11, 12, 13, 14).

The method of measurement used in this device, shown schematically in Figure 2, consists of a linear displacement transducer attached to a trailing arm, measuring displacement between the arm and a reference point. The wheel on the free end of the arm actually follows the surface profile, rather than the displacement transducer itself. This type of device can provide a continuous record of the transducer output on a simple analog recorder. However, this is not a profile. It is necessary to eliminate the response of the vehicle to the surface from the displacement measurement before an accurate representation of the profile can be obtained. This task is performed using the accelerometer.

Another profilometer system that used the concept of surface contact for measuring profile was the Air Force Weapons Laboratory LASER Profilometer (Reference 15). This profilometer did not use the same concept of measurement
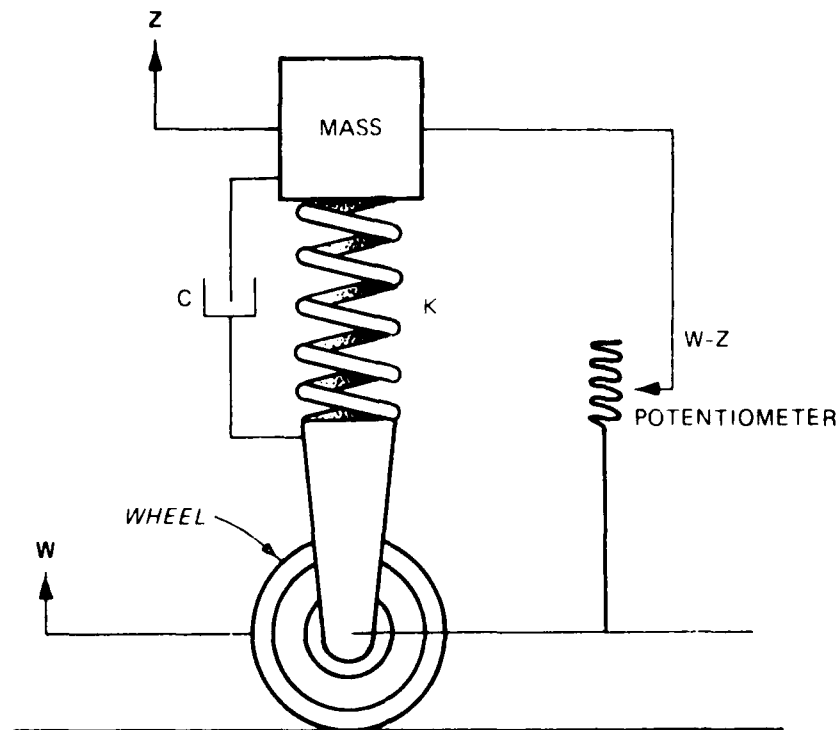
Figure 2. Principle of Surface Dynamics Profilometer.

as did the General Motors profilometer but was more like a "rolling rod and level." The system consisted of a vehicle-mounted, leveled laser and a light-sensing target connected directly to a surface-following wheel. The laser, pointing along the direction of the pavement to be profiled, remained stationary. The light-sensing target remained locked onto the laser beam and recorded the profile at 6-inch intervals as it moved up or down the rod, which traveled along the pavement surface at approximately 3 mph. This profilometer, though sound in concept, was developed when technology was not advanced enough to permit reliable, consistent profile measurement. Since that time, self-contained systems not limited by intervisibility have been developed and have rendered the concept of the LASER system obsolete.

The use of a surface-following wheel offers some significant advantages. It will filter out the very small-scale surface roughness that relates principally to skid resistance but needs to detect a step function, of the kind expected to occur on a faulted slab. The wheel described by Spangler and Kelly (Reference 9) is lightweight with a small diameter and a thin natural rubber tire. The literature shows that the road follower is not particularly robust and wears rapidly. In a recent study conducted by the University of Michigan Transportation Research Institute,* the General Motors profilometer was not run across sections that included manholes and railway

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* Sayers, M. W., Private Communication, University of Michigan Transportation Research Institute, Ann Arbor, Michigan, July 1985.

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crossings because the operators anticipated that those surfaces would severely damage the transducer.

Advances in the use of noncontact transducers have rendered this type of contact device obsolete.

2. Noncontacting Transducers

Problems with serviceability and damage to the wheel on the surface contact transducers have led to the development of noncontact displacement transducers. Three types of transducers have been investigated for use in profilometers--infrared light sources, ultrasonic sound devices, and lasers. These three transducers will be discussed separately.

a. Infrared Light Transducers

The University of Michigan Transportation Research Institute has experimented with infrared transducers while developing its profilometer. They indicated that it perceives a change in surface color as a change in height.* This is not likely to be a problem when assessing a pavement of uniform construction, such as a new asphalt or concrete runway. However, a repaired runway is likely to contain materials of several different colors, and so a system using an infrared transducer will not be suitable for use on bomb-damage-repaired surfaces.

b. Ultrasonic Transducers

Ultrasonic ranging devices have been used for widely diverse applications from automatic focusing for cameras to providing data for maneuvering supertankers into docks. The South Dakota DOT profilometer (Reference 8) uses an ultrasonic device for distance measurement, and the now-defunct company EarthTech** has also used ultrasonic transducers for profilometers.

The literature indicates two types of systems. One system, based upon the camera/automatic focus system, uses one transducer for both transmission and reception of the sound. The other uses separate transmitters and receivers.

Consider first the single transducer system. Distance from the surface to the transducer is determined from (a) the time between transmission and reception of the sound and (b) a knowledge of the velocity of sound in air. In theory, this type of system can give very high precision since the time can be measured in microseconds (μs). However, Huft (Reference 8) indicated that an uncertainty of 0.005 feet (approximately 1/16 inch) is a

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* Sayers, M. W., Private Communication, July 1985.

** EarthTech, Private Communication, 6655 Amberton Drive, Baltimore, Maryland, July 1985.

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practical limit. One other limitation of this type of system is that it imposes a horizontal limitation on the spacing between measurements. If it is assumed that the transducer is at a mean height of 1 foot above the surface, the time for the sound to travel from the transducer to the surface and back is approximately 1,800 μs. To this must be added the time during which the sound is emitted (150 μs for the South Dakota device with the same time for processing). A total of 2,500 μs would seem reasonable for a practical device. In this time, a vehicle traveling at 55 mph would cover 0.2 foot (approximately 2.5 inches). Thus, it would appear to be impractical to expect a sample spacing of less than 3 inches from this type of device when the normal spacing used by South Dakota is 1 foot (Reference 8).

It is also necessary to ensure that the sound is projected in such a way that the transducer is able to receive the reflected wave. Figure 3 illustrates this requirement assuming that the sound is projected in a conical pattern. If it is assumed that the transducer is required to be 1/2 inch inside the zone of influence of the sound footprint then the angle of the cone of sound must be approximately 14.25 degrees, creating a sound footprint of a circle of 3 inches in diameter. This will effectively eliminate the small-scale profile from the measurements and will remove any requirement for filtering. However, a step in the profile will appear as a ramp 3 inches long rather than a square wave.

The two-transducer ultrasonic system, illustrated in Figure 4, also determines distance from measurements of the time taken for a burst of sound to travel from the transmitter, reflect off the surface, and be detected by the receiver. This system also works on the basis of discrete pulses of sound, repeated at up to 100 per second, which may be regarded as continuous operation. However, for optimum performance it is necessary to tune the repetition rate to the approximate distance to be measured. This type of device can be supplied by companies such as the Massa Products Corporation of Hingham, Massachussetts. Their specification for the E-201 module, which has a range of 3 to 24 inches, indicates a potential precision of 0.001 inch. However, given the operational difficulties likely to be encountered during profile measurement, a precision of 1/16 inch, suggested by Huft (Reference 8), is probably a reasonable practical estimate.

Massa Products also recommends that the transmit and receive transducers be inclined toward each other to increase sensitivity.

Acoustical ranging devices may be subject to errors caused by ambient temperature and noise variation and the variation in the velocity of sound in turbulent air in the vicinity of the vehicle. Huft (Reference 8) indicates that this type of error appears as an apparent long-wave profile (wavelength of thousands of feet) that is not of interest to profile measurement and so can be filtered out.

The small-scale surface profile of the pavement could also be so rough that the transmitted sound would be scattered widely; thus, the return signal would be too weak for a useful measurement to be made. A porous
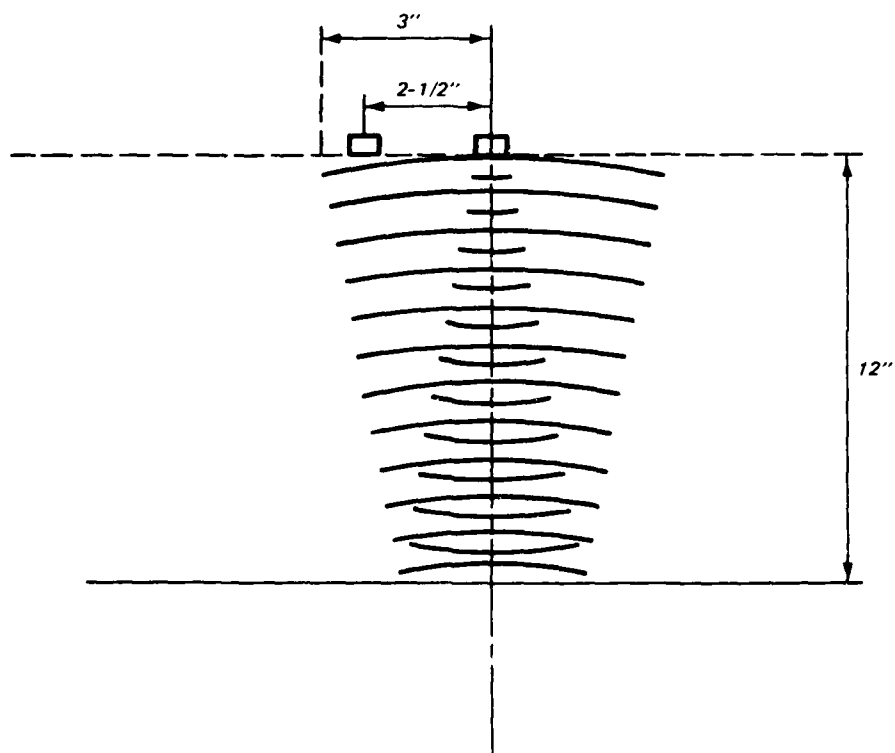
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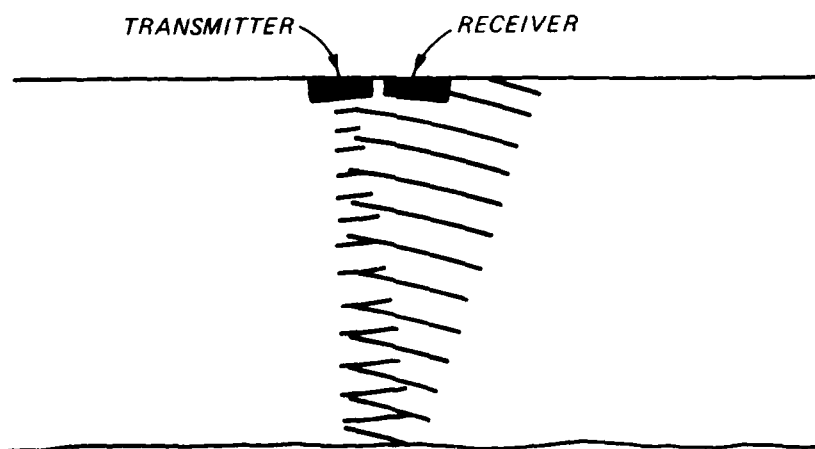**Figure 3.** Ultrasonic Transducer Operating in the Transmit and Receive Mode.

Figure 4. Ultrasonic Transducer Independent Transmitter and Receiver.

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friction surface course, commonly used on airfield pavements, could lead to loss of reflected signal. No particular difficulties of this type have been reported (Reference 8) in highway applications, but the problem potential exists.

Occasional loss of signal from surface characteristics is not difficult to handle. It can be detected by a computer-based data reduction system and marked. The user can then be permitted to decide how best to solve this problem, the usual choice being to interpolate between these values.

Another possible objection to the use of ultrasonic transducers follows from difficulties in operation in a wet environment. The South Dakota profilometer (Reference 8) is limited to operation in a dry or light mist environment. It is, however, not clear as to whether these difficulties arise as a result of extraneous noise from the interaction between vehicle tires and a wet surface or from a lack of waterproofing of the transducer. If the problem relates to waterproofing, it should be possible to overcome it without excessive difficulty. A problem related to extraneous noise may be more difficult to solve in a rapid repair environment.

Ultrasonic devices do have a distinct advantage in that they are inexpensive, costing as little as $200 for the transducer(s) plus an electronics module for providing an analog signal directly proportional to the distance from the transducer to the surface.

c. Laser Transducers

A number of pavement surface profiling devices have been constructed using laser noncontact displacement transducers (References 16, 17, 18, 19, 20).

The laser transducers all work on the same principle, which has been discussed in detail by Still and Winnett (Reference 21). The image of the illuminated area is focused onto a surface capable of discriminating the location of the image. Figure 5 shows the principle of operation using a self-scanning photoiode array as a receiver.

Laser transducers have two principal limitations as distance-measuring devices. First, insufficient light may be reflected onto the light-sensing surface to activate it; hence, a measurement will be missed. Second, the receiving optics will be unable to view the illuminated region on the surface because of shielding by the texture of the scanned surface. Measurements lost from these two causes have become known as "dropouts."

An extensive study of the effects of a wide range of surfaces has been reported (Reference 21). Table 1 is a summary of the responses of a laser transducer to these surfaces. This study indicates that the laser is not suitable for use on very rough surfaces; however, the study was carried out with a rectangular laser beam 0.0012 inch wide. This very narrow beam will penetrate the small-scale surface texture shown in Figure 1 and so will be subject to significant dropout. If a wider beam is used to produce a larger footprint, there is less likelihood of the entire beam being "lost," although this may require a redesign of the light-sensing screen.

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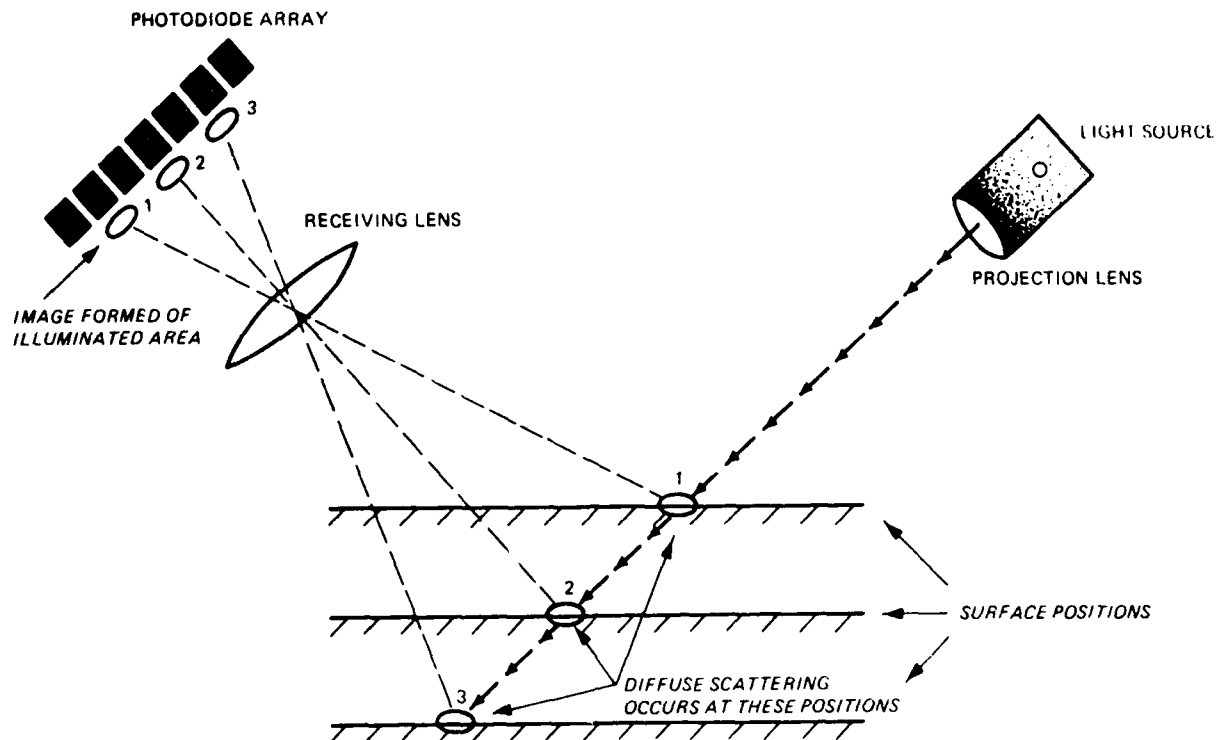
Figure 5. Basic Laser Displacement Transducer Design.

One other potential difficulty has been identified regarding the detectors used in laser devices--high-intensity ambient lighting conditions, such as very bright sunlight. Reportedly (Reference 21), a filter, centered at 0.904 µm with a bandwidth o᷈ about 0.05µ m, is effective in eliminating interference from the sun.

The precision that can be obtained with the laser transducer is about 0.001 inch, which is comparable to that of an ultrasonic transducer.

C. FILTERS

The profilometers that have been developed incorporate filters. These are used to eliminate the effects of drift of the measuring devices and also the long-wavelength components. Since most profilometers are used to provide some assessment of ride quality, the long wavelengths, which do not input any noticeable acceleration to the vehicle, can be eliminated without affecting the conclusion drawn on the basis of the measurements. However, filtering does mean that the profile produced by the device is not a representation of the surface in absolute terms. It forces the vertical displacement to remain numerically close to zero, making the long-term position appear to be a horizontal line. Thus, the measured profile is a record of the point-to-point deviation from this apparent horizontal line.

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TABLE 1. RESPONSE OF VARIOUS SURFACES TO A LASER CONTACTLESS DISPLACEMENT TRANSDUCER

Type	Code	Description	% of Readings which are dropouts	Dropout cause as a % of total dropout	
				Shielding effects	Low intensity
Concrete	A	Lightly brushed concrete	11	35	65
	B	Worn brushed concrete	0	0	0
	C	Very smooth concrete	0	0	0
	D	9 mm grooves cut in concrete	24	30	70
Bituminous materials	E	"Sheelgrip" surface dressing	23	36	64
	F	Fine-textured asphalt	2	0	100
	G	Dense tar macadam road base	56	22	78
	H	Slightly worn precoated chippings surface dressing	5	71	29
	I	Worn dense bitumen macadam wearing course (Aggregate: Leicester granite)	2	69	46
	J	Worn, unchipped, rolled asphalt	10	100	0
	K	Asphaltic concrete	10	38	62
	L	Surface dressing consisting of large pre-coated chippings	34	2	98
	M	Limestone macadam with very deep pits	61	100	0
Special materials for test purposes	N	Nine 3 mm chippings	1	50	50
	O	9 mm uncoated chippings set in concrete	15	16	83
	P	6 - 9 mm uncoated chippings set in concrete	11	74	26
	Q	12 - 25 mm uncoated chippings set in concrete	9	100	0

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One further and more significant effect of filtering is that it causes a differential phase shift between the various wavelengths present in the profile. It is not clear at this stage what effect this phase shift could have on the accelerations calculated within an aircraft simulated by the TAXI code.

The phase shift induced by the filter can be eliminated if the raw data are filtered in both directions, i.e., from measurement start to finish and from finish to start, and then averaged. However, this procedure means that it is not possible to produce a profile in real time.

One additional consequence of filtering relates to comparison of profiles produced by different devices. The phase shift, which is different for each device since each device has its own custom-made filter system, means that it is impossible to make a point-by-point comparison of the device outputs. To do this, it is necessary to determine the characteristics of the filter and reprocess the output to eliminate them, an almost impossible task if the filter specification and construction are unknown.

D. DISTANCE MEASUREMENT

An essential part of profile measurement is the measurement of displacement from a known location. This is because the purpose of profile measurement is to locate unacceptable areas so they can be corrected. When considering the Air Force requirement for profiles along the path of the nose wheel and each of the two main landing gears of an aircraft, distance measurement becomes very important for coordination of the longitudinal profiles measured along each of the three paths if they are measured in three separate passes.

The literature on profilometers does not devote significant space to discussion of distance measurements. However, it is possible to discern three types of distance-measuring devices:

Special measuring wheel.

Pulse transducer mounted on one of the vehicle wheels.

Device inserted into the speedometer drive.

These devices will be described individually.

1. Special Measuring Wheel

This device is sometimes called a fifth wheel. Figure 6 illustrates the device as installed on the profilometer described by Bush and Cox (Reference 22). The best precision obtained by Bush and Cox was 1 percent, i.e., 1 foot in 100, and it was not possible to achieve this on inclines. While this may be adequate for pavement evaluation based on an overall roughness value for each section tested, it is probably not good enough for coordination of three individual profiles measured along the paths followed by each gear on an aircraft. They could be displaced by several feet relative to each other,

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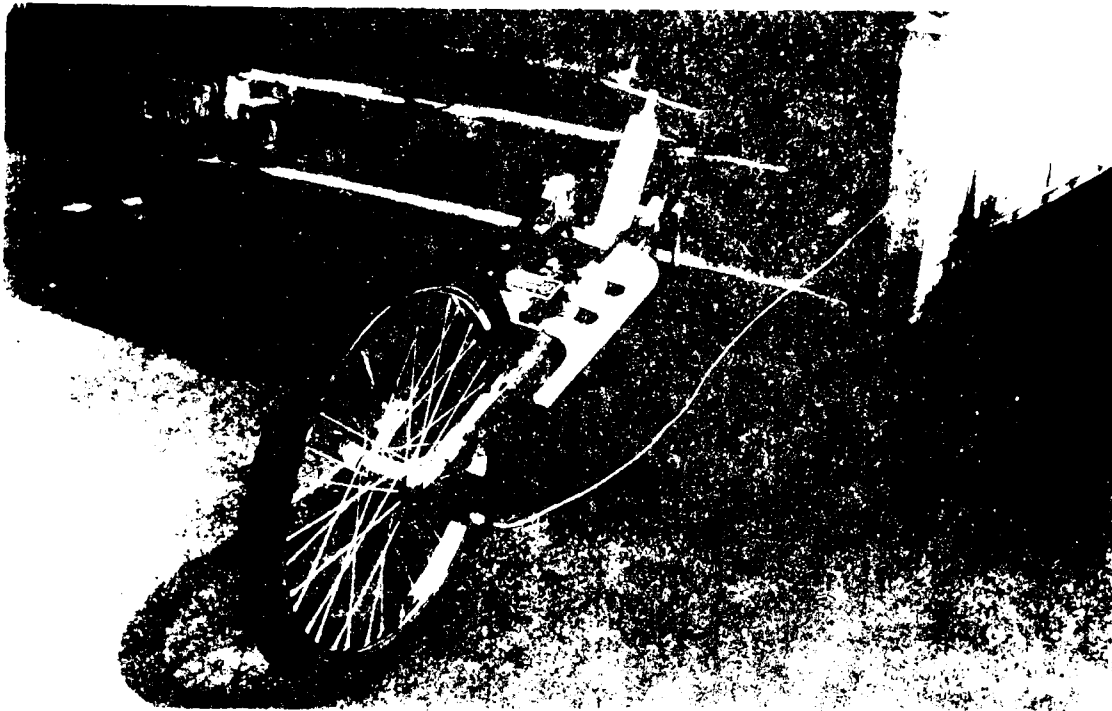
Figure 6. Fifth Wheel Installed for ... ...

since on a 5,000-foot profile ... ... ld be as much as 50 feet.

2. Pulse Transducer

It is possible ... ... distance by mounting a magnet on the wheel ... ... detector ... ... that with a coil. If necessary, several magnets ... ... pulse per rotation. The limitation of this ... ... sion with which the circumference of the wheel can ... ... ce will change with tire pressure, which is affected by ... ... quality of vehicle maintenance. ... has be ... ... that this type of system is sufficiently reliable ... ... profile measurements at 3-inch spacing.

3. Speedometer Drive ...

Sensors that can be inserted in ... ... cable are available. The speedometer drive ... ... the rear of the gearbox on automobiles. Because it ... ... drive shaft and axle to the driving wheels of the vehicle, ... similar errors and limitations of the pulse transducer. However ... ... tential errors are associated with the calibration of the ... ... transmission. This can be overcome by ... ... No data are available concerning the ... ... field profilometer application ... ... precision likely to be required in ... ...

SECTION V

PROFILE MEASURING SYSTEMS

A. INTRODUCTION

Although the transducers described in the previous section have been used in several different combinations to produce profile-measuring devices, only two devices are commercially available. All the other devices are prototypes, constructed for specific users and operated by them. Only one device appears to be available for hire, although in the past the owners of others have shown a willingness to lend their devices to competent institutions for tests and evaluation.

The purpose of this section is to describe the systems available and to consider their value with respect to the current understanding of the Air Force requirements. As indicated in the introduction, only devices capable of measuring profile will be discussed. Devices described as "ride meters" or "roughness meters" will be omitted with two exceptions. The exceptions are made because the authors think these devices could be developed to measure profiles. (Because of the prototype nature of most profilometers, it may be necessary to construct a profilometer for Phase II of this project.) Therefore, the description of the various devices below will include as much of the detail available from the literature as possible.

Table 2 lists the principal profilometers that have been developed according to the type of transducers used in them. Also noted are the manufacturer, known owners, and commercial availability.

B. PURE LASER SYSTEMS

The two pure laser systems identified in Table 2 are similar. The device described by Bush and Cox (Reference 22) is a simplified version of the Transport and Road Research Laboratory (TRRL) beam (References 16, 17), using only three lasers instead of four. Thus, it is restricted in the precision with which it measures. Also, the US Army Engineer Waterways Experiment Station (WES) device has been dismantled. Hence, the TRRL device is the only one described.

The TRRL profilometer consists of a beam approximately 14 feet 9 inches long (4.5 meters). One laser is mounted at each end, and a third in the center. The fourth laser is attached adjacent to and inboard of the laser at the leading end of the beam. The profilometer is towed behind a vehicle housing the data acquisition system and is capable of taking measurements at speeds between 3 and 50 mph.

The system developed by TRRL can measure longitudinal profile, surface texture, and groove depth and includes a digital filter for the removal of long wavelengths, which is described as a phaseless filter.

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TABLE 2. PROFILOMETERS

Measuring system	Manufacturer/ builder	Owner	Commercial availability	
			Purchase	Hire
Pure laser	Transport and Road Research Laboratory (TRRL), Gt. Britain	TRRL	No	No
	Corps of Engineers, Waterways Experiment Station	Corps of Engineers	No	No
Laser plus accelerometer	Surface Dynamics Inc./ K. J. Law, Michigan	Ohio DOT West Virginia DOT Michigan DOT Minnesota DOT	Yes	Yes
	Airport Equipment Co. AB		Yes	Yes
	University of Michigan Transportation Research Institute (UMTRI)	FHWA	No	No
Pure ultrasonic	EarthTech Inc. (no longer trading)	FHWA	No	No
Ultrasonic plus accelerometer	South Dakota DOT	South Dakota * DOT		
	Surface Dynamics Inc. Michigan		Yes	No
Pure accelerometer	University of Texas,a at Arlington	University of Texas	No	No
Mechanical	Laboratoire Central des Ponts et Chaussees, France (LCPC)	LCPC	No	No

* These two devices are presented as roughness indicators but are judged to have potential for development as low-cost profilometers.

Still and Jordan (Reference 17) have reported a detailed evaluation of the TRRL profilometer and have also given a detailed derivation of the algorithm and averaging procedure used to convert the raw data into profile. Appendix A contains the detailed derivation of the algorithm, which is not device - specific. This algorithm can be used for any similarly configured profilometer.

The study by Still and Jordan (Reference 17) included the following potential sources of error: (1) noncolinearity of transducers or profilometer beam, (2) pitching of the beam, (3) pavement geometry and crossfall, and (4) surface wetness. This study led to many comments and modifications to the system.

The most significant change concerned a lack of colinearity of the individual lasers caused by temperature gradients in the beam. This prompted the encapsulation of the whole beam with a rigid polyurethane foam. Fixed lack of colinearity, caused by imperfect mounting of the laser on the beam, was shown to introduce a parabolic error, which can be compensated for.

The principal effect of the pitching motion of the beam is to move a transducer out of its working range. This pitching motion can be alleviated by selecting the appropriate laser displacement transducer, as well as adopting operating procedures that eliminate sudden acceleration, braking, and passing over bumps (short wavelength roughness) at speeds that cause excessive vertical movement of the beam.

Road geometry and crossfall have an effect when the profilometer is required to operate on pavements that include curves. Since airfield pavements do not include curves in the same sense as highway pavements, this potential source of error does not exist.

Surface water will affect the reflection of the light from the laser. The major difficulty occurs when there is a relatively thick layer of water on the pavement. Under these conditions, the light will be reflected from the water surface and not the pavement surface, causing an uncorrectable error. Therefore, the profilometer should not be operated during rainfall but can be used as soon as the surplus water has drained away.

Concerning the precision with which the profile can be measured, the greatest errors are (Reference 17): for features less than 10 feet long, 0.06 inch; 30 feet long, 0.08 inch; and 80 feet long, 0.17 inch.

In their evaluation of the laser-beam-type device, Bush and Cox (Reference 22) made several suggestions for improving the precision of the device. One was to increase the number of transducers that would increase the redundancy of the system, thereby improving precision. Another was to add an accelerometer to the system to determine the position of the beam with respect to datum.

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C. LASER-PLUS ACCELEROMETER

The principle of operation of this type of device can be described by considering the response of a vehicle to a step in a pavement. While traveling along a smooth surface, the vehicle body keeps an equilibrium position at some distance above the roadway surface. When a step is encountered, the vehicle body is displaced and assumes a damped periodic motion until it returns to its equilibrium position. The path of a point on the vehicle body is described by the function u(x) where x is the distance coordinate and u is the distance above a fixed datum.

The distance between the vehicle and the pavement h(x) depends upon both the profile and the vehicle motion, as shown in Figure 7. From this figure it is apparent that the height of the vehicle above the surface profile at any position x is the difference between the vehicle position u(x) and the roadway profile z(x) ; i.e.,

$$h(x) = u(x) - z(x). \qquad (1)$$

$$z(x) = u(x) - h(x)$$
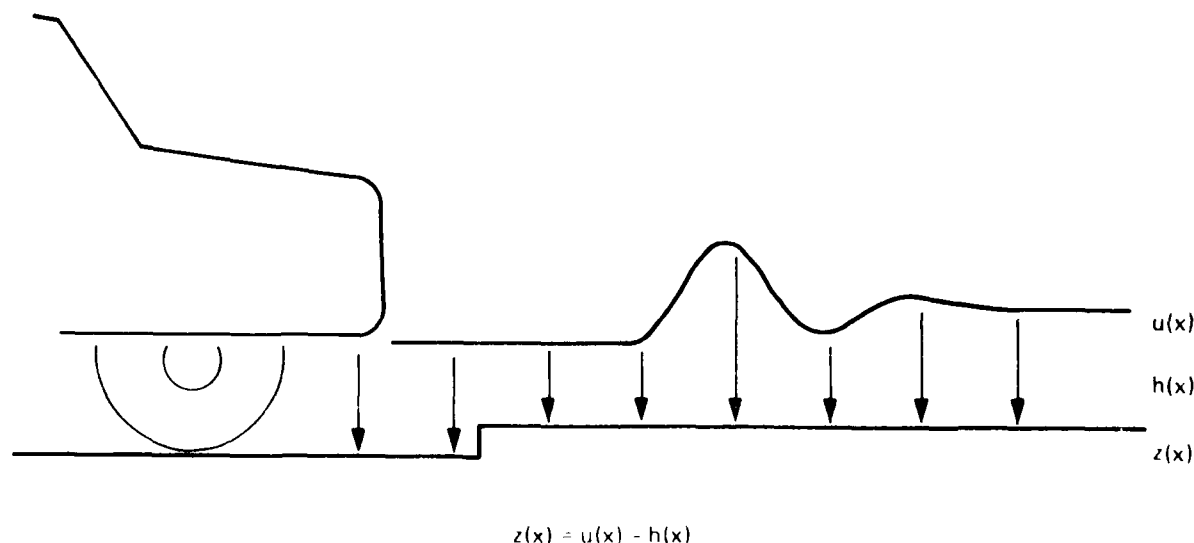
Figure 7. Profile Measurement Principle.

The vertical position of the vehicle u(x) is measured by the accelerometer. Acceleration is a function of time, so the measurements are time based, not distance based. Thus, the vertical position of the vehicle is obtained from a double integration of the displacement use: with respect to time; i.e.,

$$u(t) = \iint a(t)dt^2 \qquad (2)$$

The distance between the vehicle and the surface is measured directly by the laser, so both the terms in Equation (1) are known, and the profile can be computed.

As indicated, three devices developed for profile measurement use this principle, two of which are highly sophisticated. These devices are described as follows.

1. Airport Equipment Company, LASER RST

This device is described in some detail by Novak (Reference 19), and is illustrated in Figure 8. This device is very sophisticated and claims to measure transverse profile over and 11-foot width, crack depth and count, and surface texture. Novak reports that the tester indicates roughness, but some of the literature sent to the authors about this machine includes plots of longitudinal profile and even a 3-D plot of the surface. Thus, while profile measurement may not be the primary objective that the designers had in mind when constructing the machine, it does have the capability to measure profiles. The photograph of the device in Figure 8 shows the RST fitted with additional guidance equipment that could be of value in operating on a runway when it is necessary to follow a specific wheel path.

Figure 8.   The Swedish Laser RST.

The information available does not indicate which laser provides information on the height of the vehicle above the surface for combination with the accelerometer data. An average of the cross profile could be used, but this would not be satisfactory for the application currently envisi.... the Air Force. The device can operate at speeds between 18 and 55 mi/h and can measure rut depth to a precision of +0.04 inch. Novak (Reference 19) reports

measurements on 50,000 test sections; however, the RST did not provide data for the recent comparative study of profilometers performed for the FHWA by the University of Michigan Transportation Research Institute (UMTRI).*

2.   FHWA Profilometer Constructed by UMTRI

This profilometer consists of one laser, one accelerometer, and an IBM PC for data storage. It has been used for profile measurement in the comparative study of profilometers (Reference 20). However, it is, as yet, incomplete and so must be regarded as a prototype. The final report to the FHWA is expected to be completed by the end of August 1986. The information available on this profilometer indicates that it will measure profile with a high degree of precision; however, there are no details of the operational limits of the device. Use of an accelerometer certainly means that it will not function adequately at very low speeds. Further investigation of this profilometer is warranted because of its relatively low cost, about $40,000. The final report to the FHWA should become available early in Phase II of this project.

3.   Surface Dynamics/J. K. Law Model 690DNC Profilometer

This is probably the best known profilometer in the United States. It was originally known as the General Motors profilometer (Reference 9) and was subsequently marketed by Law Engineers. In its original form, the profilometer used a wheel attached to a potentiometer to follow the surface. As noted previously, the following wheel is prone to damage. As laser technology developed, the wheel was replaced by a laser noncontact transducer.

As with the Laser RST, this profilometer is orientated toward testing highway pavements. It is equipped with data storage and processing equipment suitable for testing a considerable length of highway for determining roughness-type parameters developed for highways. The equipment produces two profiles in real time, one in each wheel path of the vehicle. Measurements are made at 1-inch spacing, averaged over a running 12-inch interval, and recorded as profile points every 6 inches.

The recommended operating speeds are between 10 and 55 mi/h. However, the greatest wavelength that can be recorded is a function of vehicle speed, being 300 feet at 10 mi/h. The storage resolution of the system is quoted as $\pm$0.001 inch; however, from examination of the data on precision of laser devices and accelerometers, the profile is unlikely to be measured to this precision.

In its standard configuration, this profilometer provides more information than is needed to meet the Air Force requirement. The high cost of the device makes it unsuitable in its current form. However, the laser-accelerometer unit, which has performed very well in comparative tests,* could be used in a simplified profilometer.

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*   Sayers, M. W., Private Communication, July 1985.

D. PURE ULTRASONIC DEVICE

A profilometer for measuring pavement smoothness during construction was described by Bloom and Schwartz (Reference 23) at the 1984 Annual Meeting of the Transportation Research Board. This device was developed under contract to the FHWA by EarthTech, Inc. Unfortunately EarthTech, Inc., is no longer trading. The device is in prototype form and was to undergo trials in Louisiana on a paving contract in September 1985.*

This ultrasonic profilometer has five sensors mounted on a 10-foot beam, as shown in Figure 9. The complete system consists of four beams that can be mounted on finishing equipment at the rear of the concrete paving operation or directly on the paving machine. The profilometer includes a computer for data processing to provide a profile in real time. Since the profilometer is designed to provide data during pavement construction, it is meant to operate at very low speeds. The data acquisition and processing system is set up to meet this requirement. Measurements are taken at 2-inch intervals along the pavement. The specification for the profilometer indicates resolution of approximately 0.04 inch.
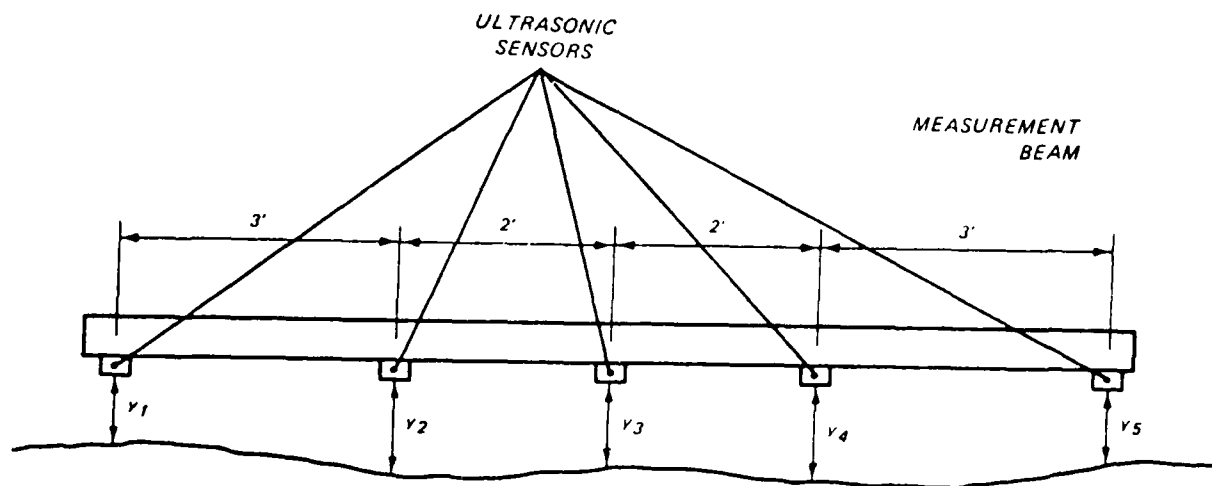
Figure 9. Ultrasonic Beam Profilometer.

Bloom and Schwartz (Reference 23) do not report any details of the algorithm that they use to determine profile. However, they do report the use of a mid-chord offset (MCO) derived from the use of a simple straightedge. In this case, the MCO is the distance from the center of the straightedge to the surface.

This profilometer will not meet Air Force requirements in its existing

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* Mitchell, T. M., Private Communication, Construction, Maintenance and Environmental Design Division, Federal Highways Administration.

configuration. However, a simplified version of this device with one beam and a data acquisition system capable of operating at relatively high speed would meet most Air Force requirements and would be inexpensive. In view of the fact that EarthTech is no longer trading and if a decision is made to evaluate this type of system, a device will hav to be specially built.

E. ULTRASONIC-PLUS ACCELEROMETER

Two devices fit this category, one described by Huft (Reference 8), the other by Law (Reference 24). The device described by Law is not presented as a profilometer. It is designed to produce a roughness index. However, the limitation on Law's Model 8300 device is the power of the computer. Since other devices using an accelerometer and a noncontact displacement transducer have been successfully developed, it should be possible to upgrade this device.

The ultrasonic-plus accelerometer profilometer works on precisely the same principle as the laser-plus accelerometer with the height measurement being provided by the ultrasonic transducer rather than the laser. It is, therefore, subject to the same limitations concerning operation as the companion device. However, the ultrasonic displacement device, costing about $300, is significantly less expensive than the lasers, which cost approximately $18,000 ($12,000 for the laser plus $6,000 for the associated electronics). Figure 10, which could also be applied to the laser plus accelerometer devices, describes the system.

One significant difference between the two devices is that the South Dakota profilometer collects data at spacings of 1 foot, longitudinally, while the Model 8300 collects data at 1-inch spacings.

Both these devices can provide low-cost profile measurement; however, the South Dakota device is a one-of-a-kind device built by the Highway Department, and the Model 8300 would require modification.

F. PURE ACCELEROMETER

This device, described by Walker (Reference 25), has not been developed to the point of providing a profile. However, it should be considered for further investigation because of its very low cost.

The accelerometer can be mounted in any convenient vehicle. The need for direct measurement of distance between the vehicle and the pavement surface is eliminated if it is assumed that the random elements in the acceleration data obtained after traversing a section of pavement are representative of the profile, and repetitive elements are from the vehicle suspension. Using this technique, the vehicle carrying the profilometer is driven over a section of road for the purpose of calibration. The calibration can then be stored, and the system is set up for measurement.

While this system has potential as a low-cost device, it does have some limitations. It cannot operate at low speed, a limitation applying to all profilometers which use accelerometers. Also, when testing concrete

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VEHICLE MOTION

ANALOG MEASUREMENT

NUMERICAL COMPUTATION

ACCELEROMETER

LOW-PASS FILTER (25 Hz)

ANALOG/DIGITAL CONVERSION (125 Hz)

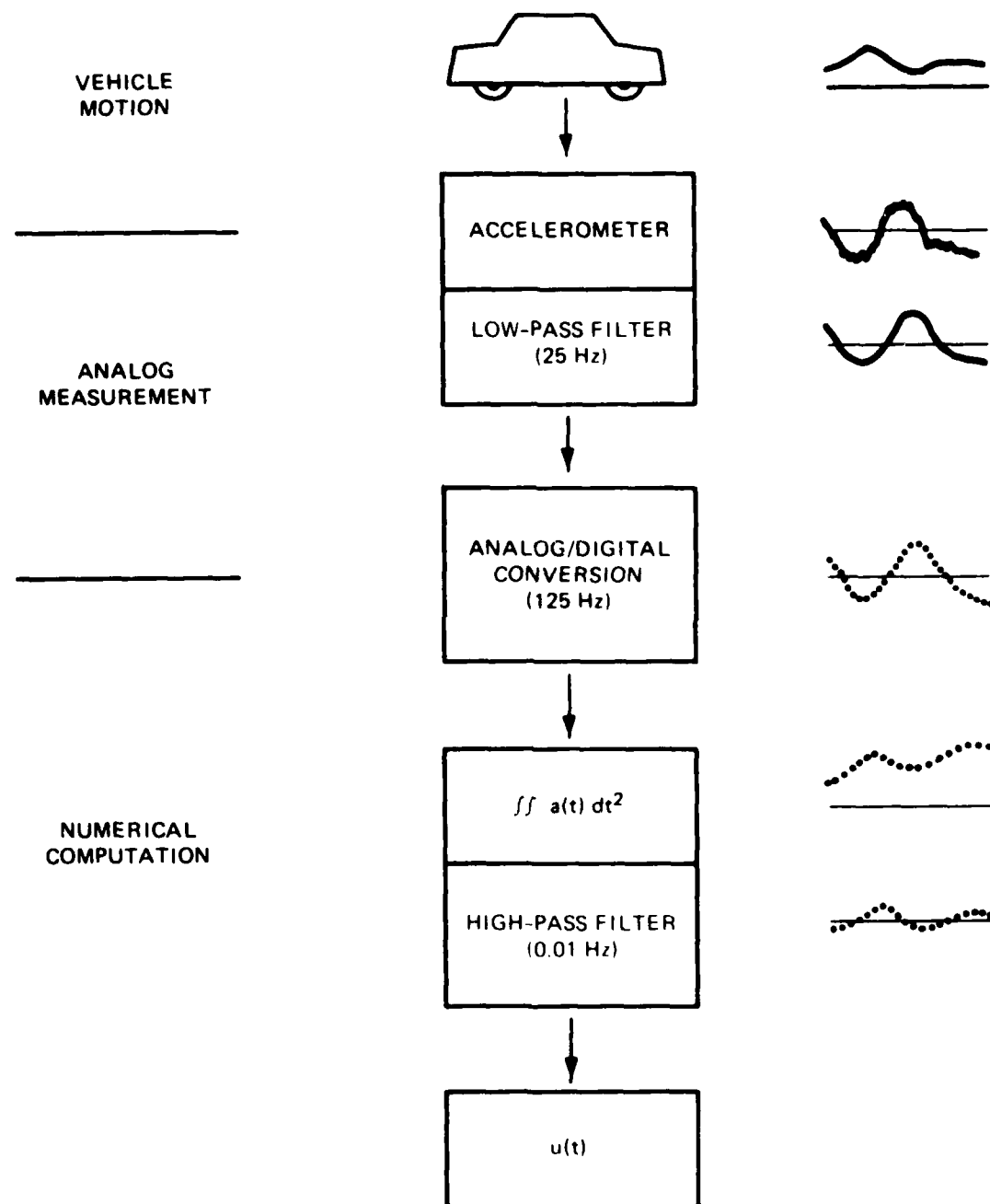$\iint a(t)\,dt^2$

HIGH-PASS FILTER (0.01 Hz)

u(t)

Figure 10. Measurement of Vehicle Position.

pavements, the joints will appear as a repetitive response, which the system, unless modified, would disregard. However, the potentially low cost of this type of system makes it an attractive proposition, since most of the other devices described so far would also need modification and development.

G. MECHANICAL PROFILOMETER

This device known as APL (Longitudinal Profile Analyzer) was developed by the Laboratoire Central des Ponts et Chaussees, France, and has been in operation for approximately 10 years. It is a trailer device, towed by a vehicle carrying the recording unit. The profilometer is shown diagramatically in Figure 11.
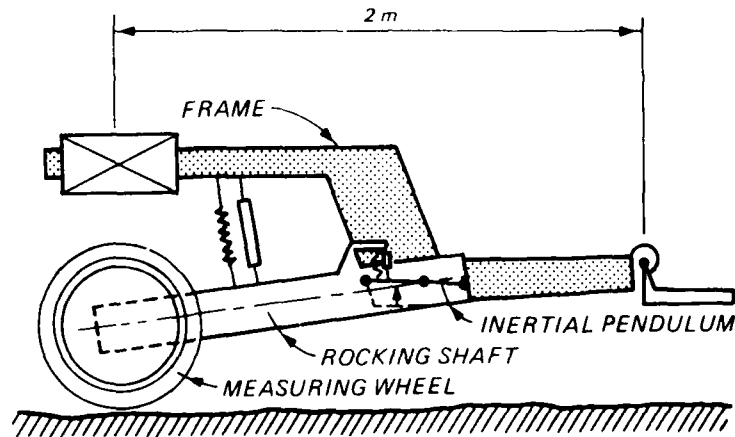
Figure 11.   Diagram of the APL.

The APL consists of a rocking shaft, kept in contact with the pavement by a measuring wheel and spring suspension, hinged to a ballasted frame. The frame is attached to a towing vehicle by a ball joint that statistically decouples the trailer from the towing vehicle and ensures that vertical movements of the vehicle do not affect measurements. Vertical movements of the wheel result in an angular shift of the shaft that is measured in relation to the balance beam of an inertial pendulum. An angular shift sensor is connected to the pendulum and provides the data on the surface profile. It is claimed that undulations of the wearing surface up to 4 inches can be measured with an accuracy of 0.04 inch.

The response of the APL depends on the speed of the profilometer. Figure 12, reproduced from the description presented by De Wilder (Reference 26), shows the range of wavelengths that can be detected at various speeds.

It would appear that this device could provide the type of data that would satisfy the Air Force requirements. However, no details are available regarding source of supply, procurability, or cost. It was included in the study undertaken by UMTRI (Reference 27), so it may be available in the United States.

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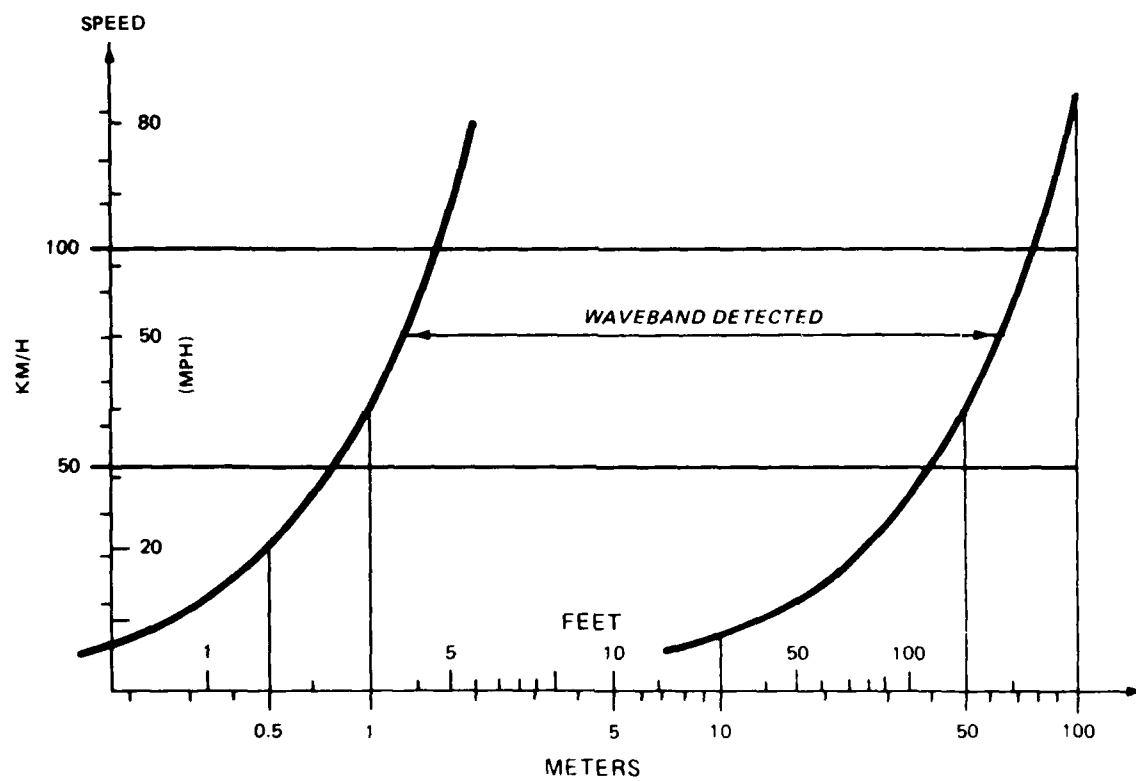
Figure 12. Range of Wavelengths Detected.

SECTION VI

MEASUREMENT OF PROFILE WITH A SERVICE LOAD ON THE PAVEMENT

It is desirable to measure profile under a representative load, since, because of the inherently variable nature of a pavement structure, the deformation from point to point along the pavement is certain to change. This will have an effect on the surface profile and could influence the response of the aircraft traveling over it. It is unlikely that load-associated deformation will produce very short wavelength roughness, i.e., in the order of inches. However, it will produce a deflection basin as small as 8 feet from side to side. Thus, a load has the potential to add roughness with wavelengths of about 8 feet or more.

The cost of increasing the mass of a profilometer to 20,000 pounds is not prohibitive. However, propelling a profilometer of this mass across a runway poses considerable difficulty, especially since it is required to operate within a restricted distance. Under these conditions acceleration and stopping distances can be significant, especially if the profilometer incorporates an accelerometer that will not function at speeds below about 10-15 mph.

Thus, it is recommended that, for practicality's sake, a relatively lightweight profilometer be used.

SECTION VII

COST OF PROFILOMETERS

Although cost data are not available for all the devices previously described, it is sometimes possible to make estimates. The following figures have been used in arriving at estimates.

Laser - $12,000 per devices + $6,000 for electronics, regardless of the number of lasers.

Accelerometer - $1,000.

Computer system - $19,000. This is based on the data in Reference 23 and the assumption that this unit would be adequate for all devices.

Large van for transportation - $25,000.

Ultrasonic transducer - $300 each.

TRRL beam profilometer. Estimate: $73,000

WES beam profilometer. Estimate: $54,000

Surface Dynamics Inc./K. J. Law. Profilometer 690CNC
$150,000-$200,000, depending on software support.

Airport Equipment Co. A. B. Estimate: $165,000

UMTRI: $36,000

EarthTech Inc. Estimate: $25,000

South Dakota: $15,400

Surface Dynamics Roughness Surveyor 8300: $40,000

University of Texas at Arlington. Estimate: $20,000*

LCPC: No price available

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* This is certainly very high because the device does not need as much computational power as the others.

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SECTION VIII

CONCLUSIONS

Neither of the two commercially available profilometers, the Law 690DNC and the Airport Equipment Co. RST, meet the requirement of providing data at low cost.

Both commercially available profilometers provide significantly more data than are necessary to meet the requirements presented by the Air Force for this project.

Two devices already developed meet some of the Air Force requirements—the South Dakota DOT device and the UMTRI prototype.

If it is assumed that the profilometer must come to rest at each end of the MOS, none of the devices reviewed can produce a complete profile. Those including accelerometers must move at least 10 mph; the others may operate at speeds as low as 3 mph.

Significant difficulties can arise with beam-type devices because of displacement of the transducer from a plane.

The technology reviewed above can be used for quality assurance and runway/airfield pavement evaluation by the Air Force.

SECTION IX

RECOMMENDATIONS

A. ADDRESS ISSUES

It is necessary to develop a more detailed specification for the profilometer. In particular, the following issues must be addressed:

> Are limitations imposed by the requirement to operate on an MOS closely defined? Is a complete end-to-end profile required? Can space be provided permitting acceleration and deceleration of the profilometer to and from operating speed?

> Must the profilometer be an independent carriage carrying the measuring and recording apparatus or can it be assumed that recording equipment can be mounted in the vehicle which may be used for propulsion?

B. CONSIDER SYSTEMS

Depending upon the resolution of the question raised above, four candidate systems may be considered. These are listed in what is estimated to be an order of increasing cost.

> *Ultrasonic displacement transducer plus accelerometer*

> Ultrasonic displacement transducers mounted on a beam

> Laser displacement transducer plus accelerometer

> Laser displacement transducers mounted on a beam

It will be necessary to determine which devices to investigate further, and since they are not commercially available, it will also be necessary to investigate potential equipment suppliers.

C. *PERFORM PARAMETER STUDIES*

Perform parameter studies using the TAXI program. These would include:

> Evaluating the data made available to WES by UMTRI from their FHWA-sponsored profilometer study.

> Determining which components (wavelengths) of a profile are critical for evaluating the safe operation of aircraft.

> Evaluating the effects of variation in data processing methodology, e.g., filtering a predicted aircraft response.

Performing a final evaluation of the profilometer with respect to the complete profile evaluation system.

D.   INVESTIGATE METHODOLOGY

Investigate methodology for coordinating profiles measured in each of the three wheel paths.

E.   PREPARE WORK PLAN

Having resolved the questions raised, prepare a detailed work plan for completion of the project.

PART II: MEASUREMENT OF PAVEMENT UPHEAVAL
ON A BOMB-DAMAGED AIRFIELD PAVEMENT

A.   INTRODUCTION

When an enemy attack occurs on a USAF airfield, returning the airfield to safe, operational capacity becomes the primary task.   Explosions leaving craters in the pavement surfaces are just one of the many problems that arise after such an attack.   An explosion creates the crater but disturbs, or upheaves, the pavement surrounding the crater.   This upheaval is not always detectable to the human eye but can be detrimental to aircraft operations when the quality of the subsequent repair of the crater is affected.

As personnel assess the situation, the need to determine the required size of repair arises.   Loose debris resulting from the explosion is removed, and measures are then taken to determine the extent of the damage.   Depending on the size of the explosion, pavement lying in the area around the crater may have to be repaired to restore aircraft operations.   For quality control, pavement surface slope and upheaval tolerances have been developed for different areas of the runway.

Currently, the Air Force determines pavement upheaval with the string line method.   This operation consists of extending a taut string from undisturbed pavement around the crater.   By measuring from the string to the pavement surface, the upheaved portion of the pavement around the crater can be determined and compared with the given tolerance (Figure 13).   Several measurements are taken about the crater to determine the extent of upheaval. The method works well in controlled situations with trained personnel, but will produce widely varied results when using untrained personnel in a rapid repair situation.   One particularly difficult situation is the existence of a crater in a vertical curve in the runway.   Because time is critical after a runway has been removed from use, a method that is accurate under wartime circumstances when used by untrained personnel is desired.   Alternatives to this method have been researched and are presented.

B.   PAVEMENT UPHEAVAL MEASUREMENT SYSTEMS

1.   Profilometer Systems

The developmental profilometer, either as-constructed or with minor adaptations, may prove capable of measuring pavement upheaval.   Two constraints on a profilometer to be used for determining pavement upheaval are (1) it must operate at low speeds and (2) it must be able either to stop or start at the crater edge.   A low-speed or even a speed-independent device is required since the area of interest for pavement upheaval is only a distance of from 2 to 20 feet radially around a crater.   This low-speed operational requirement eliminates any profilometer configuration that includes an accelerometer requiring a speed of at least 10 mph to produce a profile. Profilometers containing only a displacement transducer, whether it is surface-
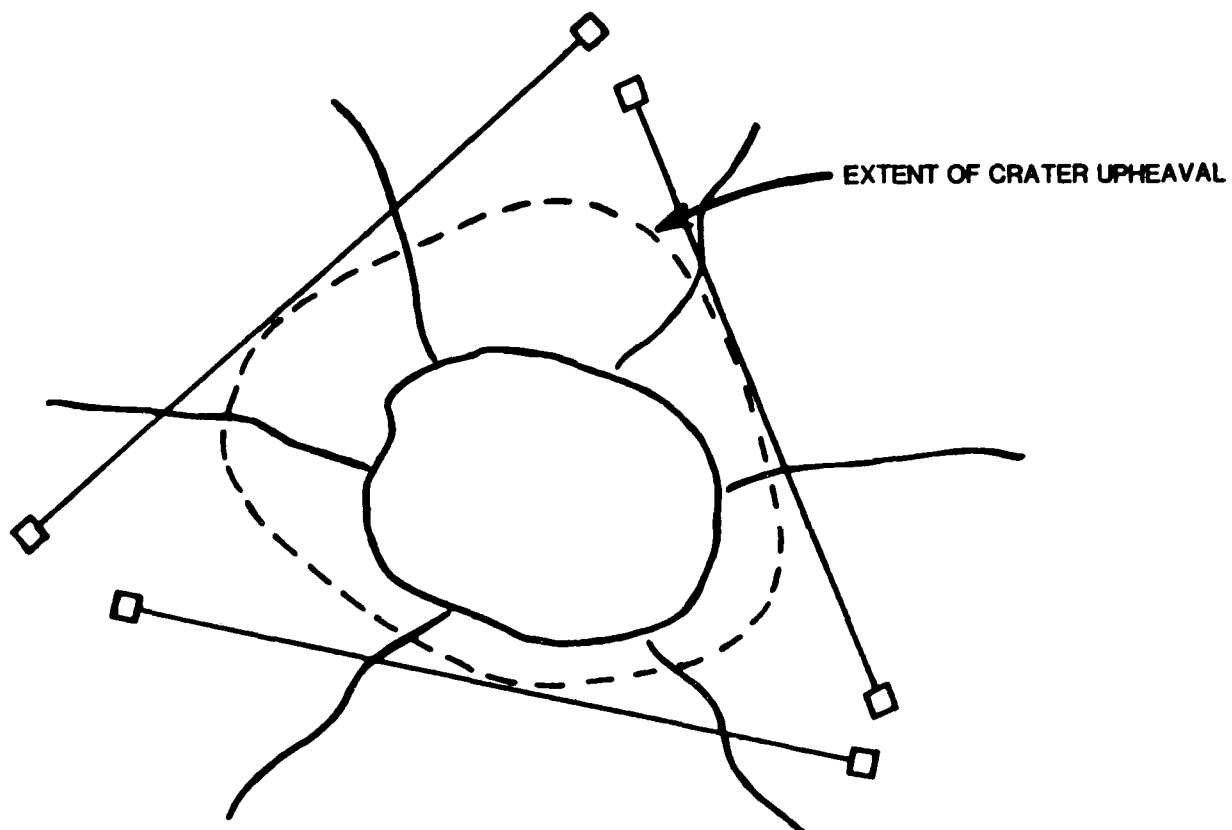
EXTENT OF CRATER UPHEAVAL

Figure 13. String Line Method.

contacting or noncontacting, may produce the profile needed to determine pavement upheaval. The filtering process found on all profilometer systems would probably have to be removed because a true profile of the area of interest is required.

Some profilometer systems examined were trailer-mounted. If the trailers are large and require a vehicle to operate, these devices would be impractical for determining pavement upheaval. Too much time would be required to align the trailer along the desired line of measurement.

2. Surveying Systems

Surveying systems, for surveying small areas of interest in short periods of time, exist. The most promising instruments available use lasers to quickly and accurately determine elevation and distance and contain small computers with software capable of receiving the information and outputting the desired results, such as profiles, in a matter of minutes. One such system, the Hewlett-Packard HP 3820-A Total Electronic Station, can store up to 500 distance and elevation readings before the downloading of information to a tape is required. The laser source is mounted on a tripod, and readings are taken as the laser reflects from a prism situated on a rod back to the instrument. Because these devices cost from $10,000 to $50,000, this type of surveying system has been excluded from further research for this application.

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The Edward W. Face Co. of Norfolk, Virginia, markets a gyroscope-based device called the Dipstick Floor Profiler, which relates the difference in elevation of two points separated by 12 inches (Figure 14). The elevation
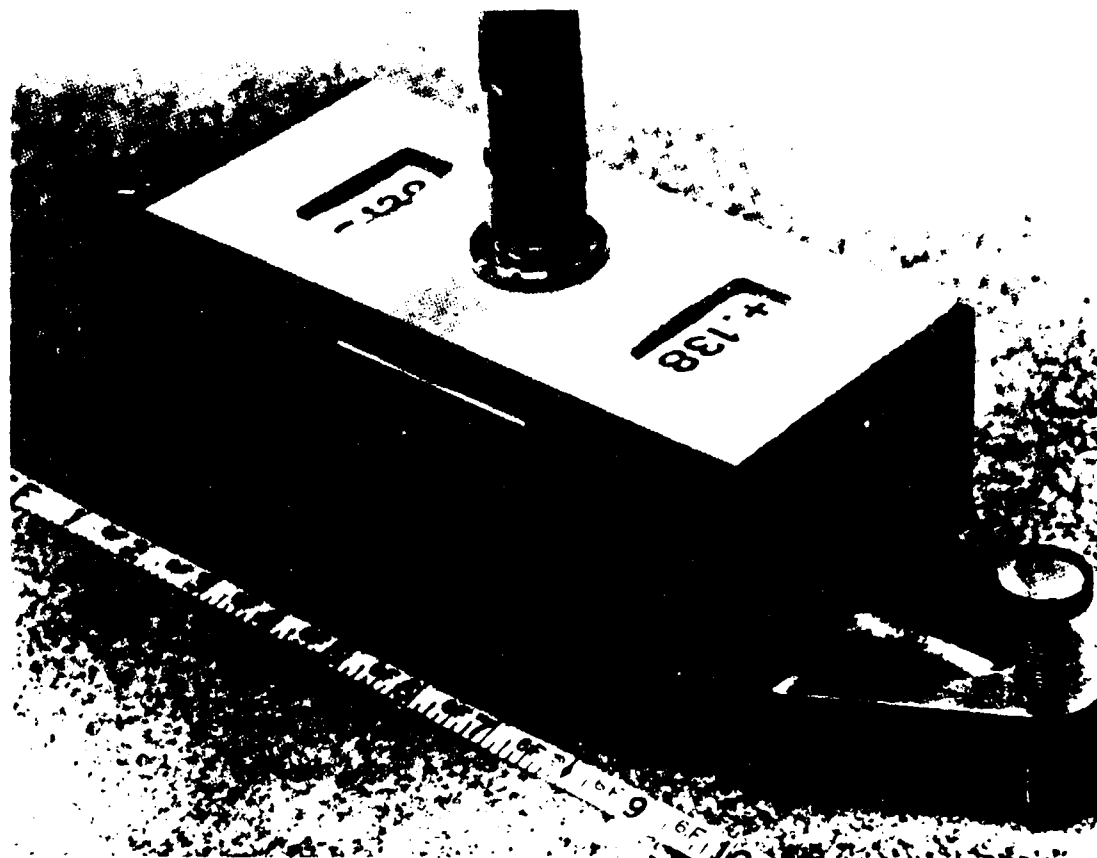
Figure 14. The Dipstick.

readings on each end of the instrument are in reference to the other end, therefore, each display reads the same value with opposite signs. To profile a line of interest, the starting point is indicated, and then the Dipstick is "walked" along the line by alternately pivoting about each leg. Taking a reading after each pivot, the data are entered into the Radio Shack PC-2 computer included in the Dipstick kit, and a true profile of the line is printed by the computer. The amount of time required to survey and analyze a 20-foot line is between 1 and 2 minutes (Reference 28). The handheld computer produces a printout of the data points, along with a plot of the actual profile, which is given on a scale relative to the size of the differences in the readings. The manufacturer indicates that the Dipstick elevation readings are accurate to within 0.002 inch.

The Dipstick has seen extensive use in industry for determining the flatness of floor slabs and is being studied by the American Concrete Association for adoption of a new standard for specifying and rating slabs

(Reference 29). The instrument is easily calibrated; the calibration is retained during storage; it can be used with minimal training. It is a durable, battery-operated device and is stored in a foam-fitted metal case. The self-contained Dipstick kit markets for $3,995.

An obvious alternative would be to retain the string line method of measurement and modify and perfect the present usage. Currently, the string line method is used around the crater to measure upheaval. A modification to the measurement technique would measure upheaval with the string intersecting the crater, not around it (Figure 15). The distance from the string to the pavement is measured, and as this distance decreases approaching the crater, the upheaved portion of the pavement could be determined. This modified string line method would measure results in the same manner as the Dipstick. This method may be able to detect crater upheaval in less time and at a lower cost.

Various "mechanical" devices, capable of swiftly and accurately measuring pavement upheaval, could be constructed. One possibility would be to level a 25-foot bar (on footings or lockable wheels), placing one end at the edge of the crater and the other end on the line of interest (Figure 16). A floating wheel attached to the bar and fixed vertically would traverse the pavement and plot a profile of the surface, either mechanically or by using collected computer data, resulting in a profile of the surface from which the critical point of upheaval could be determined.

3. Conclusions

The following conclusions have been reached concerning measurement of pavement upheaval on bomb damaged airfield pavements:

a. A low operational speed is required.

b. A system operating from a trailer would be impractical.

c. All the methods discussed appear to be capable of achieving the quick data turnaround and accurate performance required to determine pavement upheaval.

d. Some methods require research and construction to determine if the device will actually detect pavement upheaval.

e. The Dipstick has a proven work record in industry for producing limited-length profiles for the flatness of floor slabs and requires no additional development to produce the profile needed for determining pavement upheaval.

4. Recommendations

All the methods described previously can detect pavement upheaval about a bomb crater. However, without actually testing at a crater, it is impossible to determine which of the methods would prove to be the most

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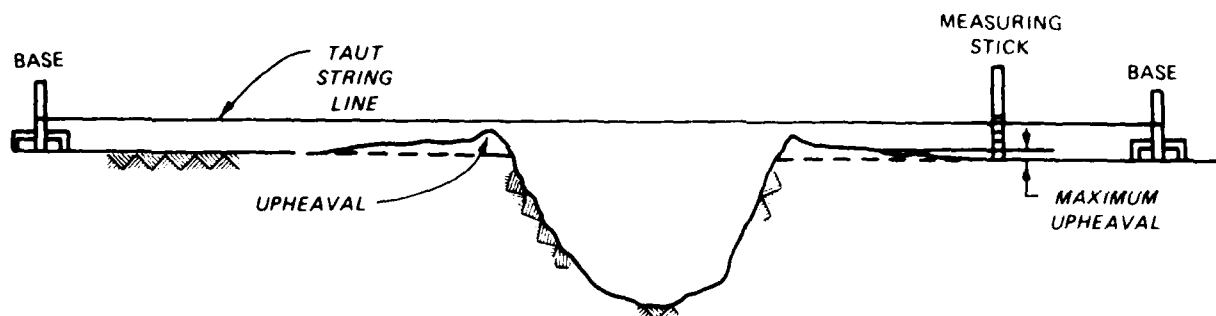
NOTE: HEIGHT OF STRING AT THE TWO BASES MUST BE THE SAME

Figure 15.   The Modified String Line Method for Measuring
Pavement Upheaval.

Figure 16.   Mechanical Instrument for Measuring Pavement Upheaval.

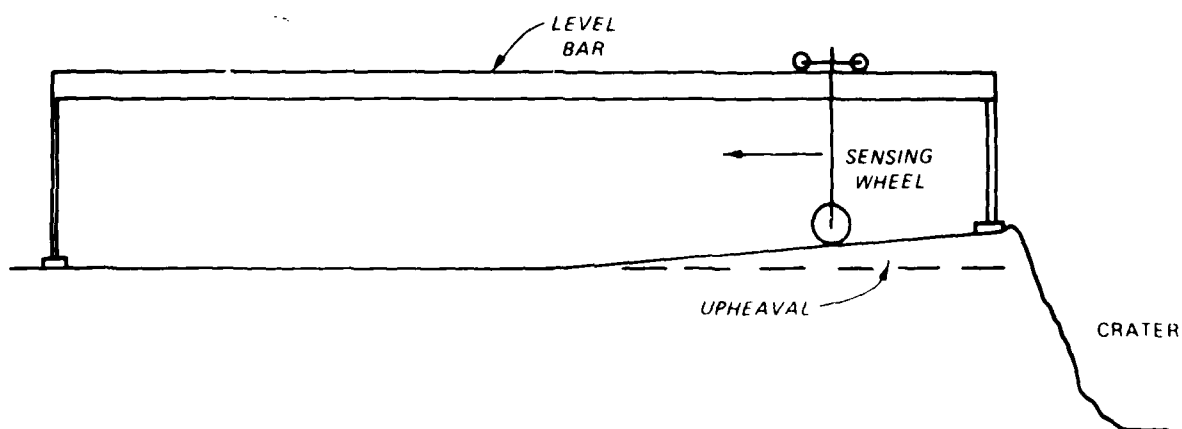efficient for upheaval detection. Therefore, it is recommended that
a test plan be carried out that will allow each method to perform crater
upheaval detection on an actual crater, so an evaluation can be made as to
which method would perform the most efficiently and accurately.

APPENDIX A

PRINCIPLE OF OPERATION OF THE TRRL HIGH-SPEED PROFILOMETER; TWO PROFILE-MEASURING SYSTEMS IN ONE PROFILOMETER DEVICE

The high-speed profilometer (HSP) incorporates two profile-measuring systems to enable a wide range of wavelengths to be measured--symmetric (SYM) and asymmetric (ASY). Pavement features with a wavelength in excess of 10 meters are measured by the SYM system which computes the average profile height over 2.14-meter sections every 2.14 meters along the pavement to provide the SYM profile. The second profile-measuring system produces the ASY profile and contains features with wavelengths in the 0.5- and 20-meter range with the computed profile measurements representing the average profile heights over 0.107-meter sections every 0.107 meters along the pavement.

A single composite profile containing all of the wavelengths measured by the two systems is obtained by restoring into the ASY profile those features measured by the SYM system.

The operation of the two profile-measuring systems is described below. The computer is programmed to calculate and to store the first differences of the profile to avoid the practical problem associated with handling large numbers that vary by small amounts. The profile is retrieved by the computer summing the first differences obtained from the start of the profile measurement.

A. SYMMETRIC SYSTEM

   1. Ideal Conditions

      The SYM profilometer consists of three displacement transducers spaced at equal distances on a rigid beam supported above the pavement profile as illustrated in Figure A-1. To explain the principle of operation, an ideal SYM system will first be considered. It is assumed that:

      a. The transducers are identical in all respects and can accurately measure distances within their working range.

      b. The pavement surface, although capable of diffusely scattering the incident laser light, is otherwise smooth (no texture).

      c. The profilometer beam is straight and rigid.

      Using such an ideal SYM system on a smooth surface, the heights h_A, h_B, and h_C of transducers 1, 2, and 3 from points A, B, and C on the surface can be accurately measured, as shown in Figure A-1. If the datum for the profile measurements is defined as the straight line passing through the surface points A and B, then the profile heights (Y) relative to this datum at points A, B, and C are, respectively:

$$Y_A = 0 \ ; \quad Y_B = 0 \ ; \quad Y_C = -(h_A - 2h_B + h_C) = U_1 \qquad (A-1)$$

where U_1 is the characteristic measurement of the SYM system.
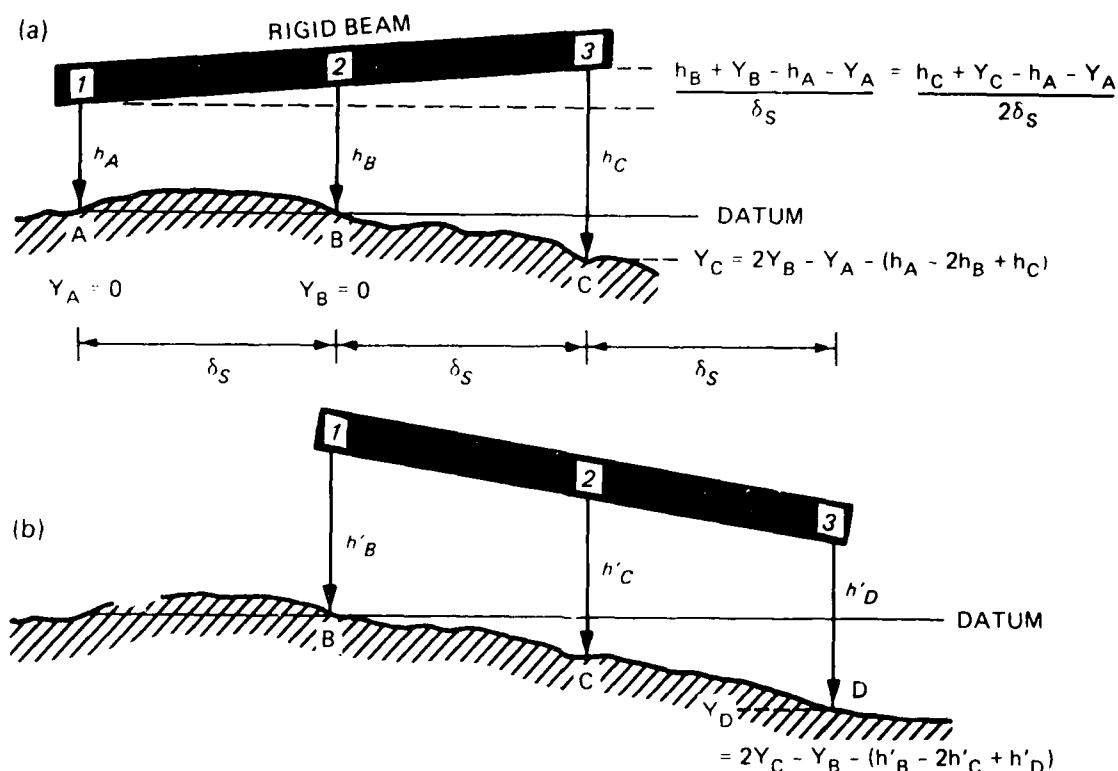
Figure A-1. Operation of an Ideal Symmetric Profilometer.

Moving the profilometer forward to a position where the laser light from Transducers 1 and 2 illuminates points B and C on the surface permits the height (Y_D) of profile point D relative to the datum through points A and B to be calculated using the new height measurement h_B, h_C, and h_D as follows:

$$Y_D = 2Y_C - Y_B - (h'_B - 2h'_C + h'_D)$$

$$= Y_C + U_1 - 0 + U_2$$

$$= Y_C + \sum_{i=1}^{2} U_i \tag{A-2}$$

where U_1 and U_2 are characteristic measurements of the SYM profile measuring system and Y_C is the height of profile point C relative to the datum through A and B. By moving the profilometer forward through successive steps, each step equal to the distances μ_S between the transducers on the SYM profile measuring system, the heights of profile points separated by distance μ_S are calculated in a manner similar to that for point D.

In general, therefore, the profile height of the nth point at distance x along the profile is given by the expression:

$$Y_x = Y_{(x-\delta_S)} + \sum_{i=1}^{n-2} U_i \qquad\qquad (A-3)$$

where $n = x/\delta_S$.

An important feature of Equation (A-3) is that the characteristic measurements U_i of the SYM system are not affected by changes in the height or pitching of the profilometer beam about the pavement surface, provided the surface remains within the working range of the transducers. Because the arbitrary datum defined for the SYM measurements may not be parallel to the axis of the actual profile, a linear trend can be introduced into the calculated profile heights. The trend produces no distortion of the measurements other than adding a constant slope to the measured profile.

Equation (A-3) involves the cumulative sum of the characteristic measurements U_i . In nonideal conditions small errors in the determination of the U_i will accumulate and can cause significant distortion of the measured profile if the magnitudes of these errors are not maintained at a very low level.

2. Nonideal Conditions

In practice, the ideal conditions assumed in the derivation of the equations for the SYM profile-measuring system cannot be achieved because (1) pavements are always textured and the transducer has a finite resolution for a single displacement measurement, (2) it is not possible to ensure that the two rear transducers of the SYM system will, on being moved forward through a step length δ_S , exactly illuminate the same surface points measured by the front two transducers in the previous measurement position of the profilometer, and (3) small errors in the displacement calibration factors of the individual transducers and/or curvature of the profilometer beam can distort the measured profile.

To reduce the effect of factors (1) and (2) above on the profile measured by the SYM system, the displacements measured by each transducer as the profilometer moves through a distance δ_S over the surface are averaged. Thus, the individual displacement measurements used to derive the characteristic SYM measurements U_i in Equation (A-3) are replaced by the averaged displacements (see Figure A-2), and Equation (A-3) now becomes:

$$\bar{Y}_x = \bar{Y}_{(x-\delta_S)} + \sum_{i=1}^{n-2} \bar{U}_i \qquad\qquad (A-4)$$

where $\bar{Y}$ and $\bar{U}$ represent the values averaged over a distance δ_S . The subscripts x and $x-\delta_S$ now refer to the midpoints of the step lengths δ_S , over which the averages have been calculated.
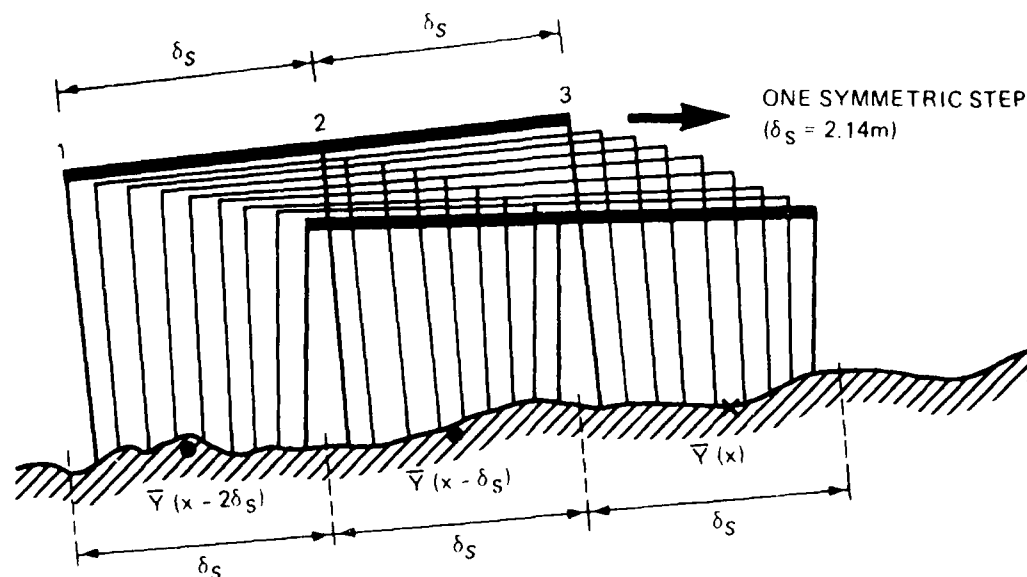
Figure A-2. Operation of a Practical Symmetric Profilometer.

The heights $\overline{Y}_x$ in Equation (A-4) are not those of the actual profile but of the profile smoothed by a moving-average of length δ_S. Consequently, the amplitude of profile features of wavelength less than 5 δ_S are attenuated in the measurements of the SYM profile-measuring system. To restore the short wavelength features of the profile, the measurements made by the ASY profile-measuring component of the profilometer are used.

Although the averaging technique described above ensures an adequate long-wave response from the profilometer, the effects of the factors listed are not eliminated completely from the profile measured by the SYM system. The residual effects of the factors on the accuracy of measurement and long-wave response of the SYM system are discussed later.

B. ASYMMETRIC SYSTEM

1. Ideal Conditions

The ASY profile-measuring system consists of three displacement transducers positioned on the profilometer beam, as shown in Figure A-3. Transducers 1 and 3 are common to both the SYM and the ASY system. The spacing δ_A of Transducers 3 and 4 is 1/40 of the distance between Transducers 1 and 3. In describing the principle of operation of the ASY system, assumptions similar to those considered for the ideal measurements of the SYM system are made.

With such ideal conditions, the ASY system can measure the heights h_A, h_B, and h_C of Transducers 1, 4, and 3 from points A, B, and C on the surface, as shown in (a) of Figure A-3. If the datum for the ASY profile measurements is defined as the straight line passing through the surface points A and B, then the profile heights Y relative to this datum are, respectively:
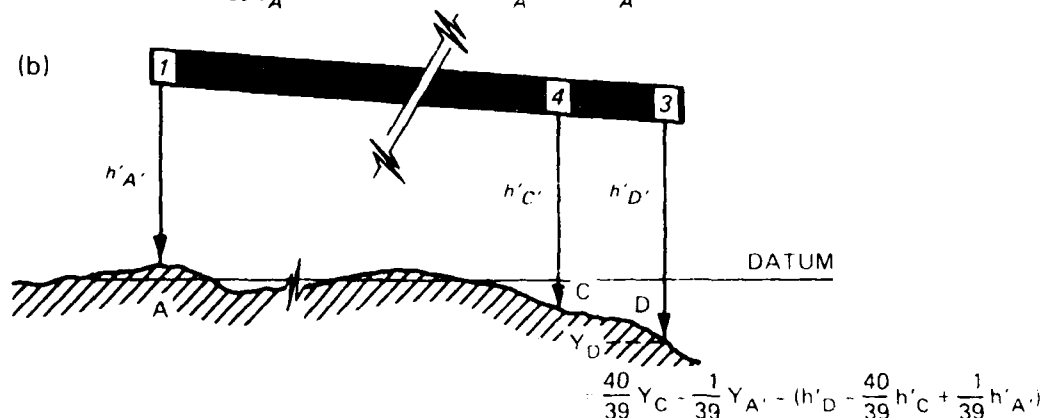
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(a)

$$\frac{h_B + Y_B \quad h_A \quad Y_A}{39\,\delta_A} \qquad \frac{h_C + Y_C \quad h_A \quad Y_A}{40\,\delta_A}$$

DATUM

$$- \ Y_C = \frac{40}{39}\ Y_B - \frac{1}{39}\ Y_A - (h_C - \frac{40}{39}\ h_B + \frac{1}{39}\ h_A)$$

$Y_A = 0$ $Y_B = 0$

(b)

DATUM

$$\frac{40}{39}\ Y_C - \frac{1}{39}\ Y_{A'} - (h'_D - \frac{40}{39}\ h'_C + \frac{1}{39}\ h'_{A'})$$
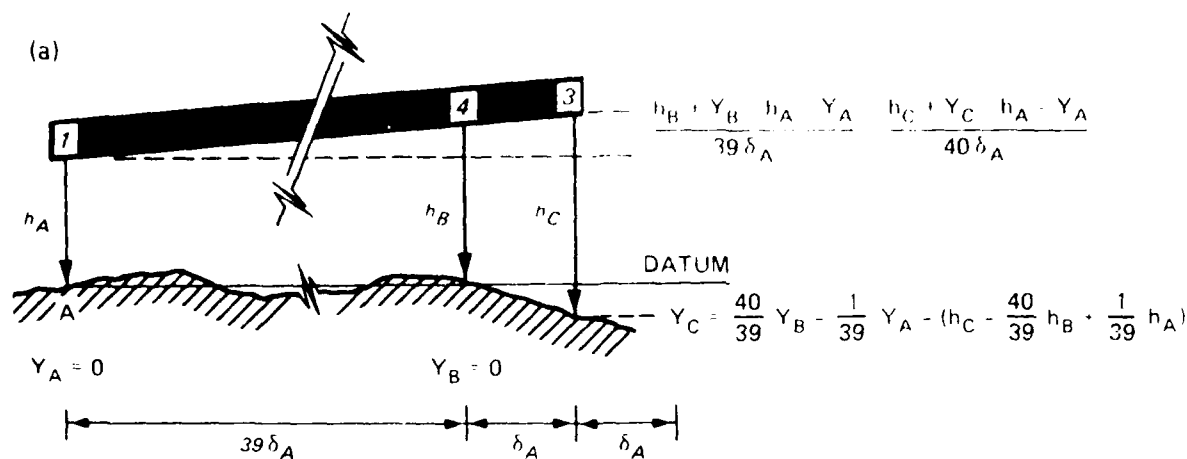
Figure A-3.   Operation of an Ideal Asymmetric Profilometer.

$$Y_A = 0\ ; \quad Y_B = 0\ ; \quad Y_C = \frac{40}{39}\ Y_B - \frac{1}{39}\ Y_A + W_1 \qquad\qquad (A-5)$$

where W_1 is the characteristic measurement of the ASY system and is given by the expression:

$$W_1 = -\left(h_C - \frac{40}{39}\ h_B + \frac{1}{39}\ h_A\right) \qquad\qquad (A-6)$$

Moving the profilometer forward through distance $_A$, such that Transducer 4 illuminates Point C on the surface, the height Y_D of Point D relative to the datum through A and B is obtained from the expression:

$$Y_D = \frac{40}{39}\ Y_C - \frac{1}{39}\ Y_{A'} + W_2 \qquad\qquad (A-7)$$

where $W_2 = -\left(h'_D - \frac{40}{39}\ h'_C + \frac{1}{39}\ h'_{A'}\right)$

The heights h'_D , h'_C , and $h'_{A'}$ are the new displacement measurements of transducers 3, 4, and 1, respectively, as shown in (b) of Figure A-3. By moving the profilometer forward in this manner through steps of length δ_A , the

profile heights at points separated by δ_A may be calculated, and the general expression for the profile point at distance x along the profile is given by:

$$Y_x = \frac{40}{39} Y_{(s-\delta_A)} - \frac{1}{39} Y_{(x-40\delta_A)} + W_x \qquad (A-8)$$

The characteristic measurement W_x of the ASY system is, like that of the SYM system, not affected by changes in height or pitching of the profilometer beam relative to the surface, provided that the surface remains within the working range of the transducers. Also, the ASY measurements, like those of the SYM system, may include a linear trend; the trend is caused, as in the SYM measurements, by the adoption of an arbitrary datum that may not be parallel to the axis of the actual profile.

The profile heights relative to the arbitrary datum AB are, in general, not zero between Points A and B. However, at the beginning of a survey these profile heights are not known and are taken to be zero over the first 39 step lengths δ_A of the ASY measurements. Thus, some error is introduced into the measured profile of the short length of pavement immediately beyond the commencement of the measurement.

Computer simulation studies of the operation of the ASY system have shown that the length of profile affected by this distortion is less than 50 meters.

In practice, this distortion does not present a problem, as a profile measurement can be started a distance in advance of the profile section to be measured; this distance is chosen to equal or exceed the length of 50 meters.

2. Nonideal Conditions

In the practical operation of the ASY system, the ideal conditions assumed above are not met. The factors that influence the accuracy of the ASY system under practical operating conditions are similar to those described for the SYM system above.

The method adopted to reduce the effect of these factors on the ASY measurements is also similar to that used on the SYM measurements. The displacements, measured by each transducer of the ASY system on moving through a step length δ_A are averaged, as shown in Figure A-4. Consequently, the expression from Equation (A-8) for the profile measurements Y of the ASY system now becomes:

$$\bar{Y}_x = \frac{40}{39} \bar{Y}_{(x-\delta_A)} - \frac{1}{39} \bar{Y}_{(x-40\delta_A)} + \bar{W}_x$$

where $\bar{Y}$ and $\bar{W}$ represent the average values over a step length $_A$; the subscripts refer to the midpoint of the step length δ_A over which the averages have been calculated. The profile heights $\bar{Y}_x^A$, given by Equation (A-9), are those of the actual profile smoothed by a moving-average of length δ_A.
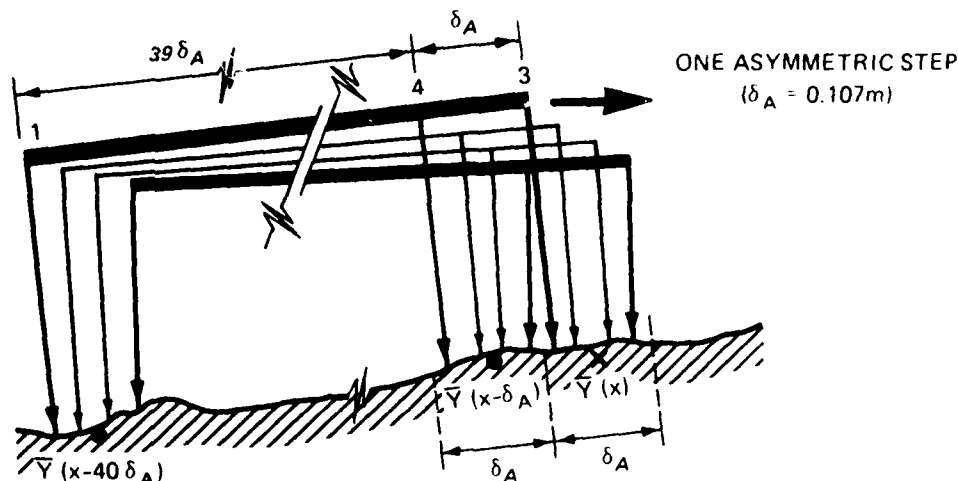
Figure A-4. Operation of a Practical Asymmetric Profilometer.

Because of the reduced averaging length δ_A used in Equation (A-9), relative to that adopted in Equation (A-4) for the SYM system, the residual errors in ASY measurements are greater tnan those in the SYM measurements. However, these errors mainly affect the longer wavelength measurements of the ASY system. As these long waves are measured more accurately by the SYM system, a digital filter with a cutoff wavelength of 20 meters is incorporated in the ASY calculations to remove the longer wavelengths.

The filtering introduces some phase distortion into profiles measured by the ASY system, particularly in wavelengths near to the filter cutoff wavelength of 20 meters. This phase distortion is, for all practical purposes, removed from the final profile by the restoration process described in the following section.

C. RESTORATION PROCESS

The SYM and ASY profile-measuring systems described above produce two versions of the same actual profile; the SYM profile contains relatively accurate long-wave features but with the amplitudes of the short waves attenuated. In the ASY profile, the converse is the case. A composite profile containing both the long and short wavelengths is obtained by reshaping the ASY profile using the SYM profile, as described below.

The length used in the reshaping procedure is the SYM measurement-step length δ_S , which is equivalent to 20 measurement-step lengths δ_A of the ASY system. The reshaping procedure depends upon the fact that the SYM profile points are derived from exactly the same actual profile as the ASY profile points. Therefore, averages computed from ASY measurements, over length 20 δ_A of the profile that corresponds exactly to the step length δ_S of the SYM measurements, should give an identical pattern to that of the SYM profile. Where the two patterns differ, the more accurate SYM measurements are used to reshape the pattern provided by the average ASY measurements. This procedure restores the long-wave features to the profile measured by the ASY system.

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The principle of the restoration procedure is illustrated in Figure A-5. Figure A-5 (a) shows an actual profile, and the measurements $\bar{Y}_S$ of the profile by the SYM system are shown in Figure A-5 (b). The ASY profile measurements $\bar{Y}_A$ and their averages $\bar{\bar{Y}}_A$ over SYM step length δ_S are given in Figure A-5 (c). By means of the following slope and offset corrections, the ASY measurements $\bar{Y}_A$ are adjusted so that the adjusted ASY measurements $\bar{Y}_R$ averaged over length δ_S give an identical pattern to that of the SYM points $\bar{Y}_S$.

$$\text{Slope correction} = \left\{ \left[\bar{Y}_S(j) - \bar{Y}_S(j-1) \right] - \left[\bar{\bar{Y}}_A(j) - \bar{\bar{Y}}_A(j-1) \right] \right\} \left(\frac{\delta_A}{\delta_S} \right) i$$

$$\text{offset correction} = \bar{Y}_R(k) - \bar{Y}_A(k)$$

therefore,
$$\bar{Y}_R(\ell) = \bar{Y}_A(\ell) + \bar{Y}_R(k) - \bar{Y}_A(k) \tag{A-10}$$
$$+ \left\{ \left[\bar{Y}_S(j) - \bar{Y}_S(j-1) - \bar{\bar{Y}}_A(j) - \bar{\bar{Y}}_A(j-1) \right] \right\} \left(\frac{\delta_A}{\delta_S} \right) i$$

where i is the location of the ASY measurement within each length δ_S and ranges from $i = 1, 2 \ldots$ to δ_S/δ_A , and j defines the location of the length being adjusted. k and ℓ are given by the equations:

$$k = (j - 3/2) \frac{\delta_S}{\delta_A} \quad j \geq 2 \tag{A-11}$$
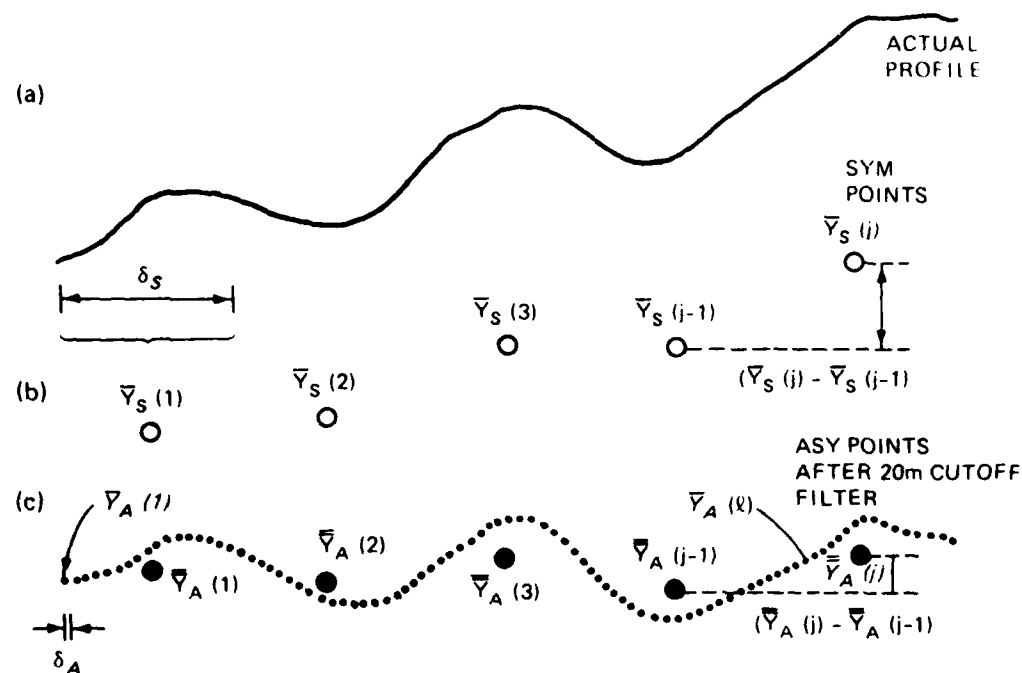
$$\ell = k + i \tag{A-12}$$

$$\text{and} \quad \bar{Y}_R(k) = \bar{Y}_A(k) \quad \text{for } k = 10 \tag{A-13}$$

The spacing of the points $\bar{Y}_R$ along the restored profile is δ_A , the same spacing as that of the ASY measurements $\bar{Y}_A$. Though the assumption of a linear correction over each piece length δ_S is an approximation to the true correction required, computer simulation studies, together with comparisons of surveyed and profilometer-measured profiles, have shown that the distortion arising from the use of this procedure is negligible. The results of these comparisons are discussed later.

As described above, the first differences of the calculated profile are used in the profilometer system to overcome the practical problem associated with the processing of large numbers. Thus, the first difference form of Equation (A-10) is used in the profilometer, and it is given by:

$$\bar{Y}_R(\ell) = \bar{Y}_A(\ell) + \left[\bar{Y}_S(j) - \bar{\bar{Y}}_A(j) \right] \left(\frac{\delta_A}{\delta_S} \right) \tag{A-14}$$
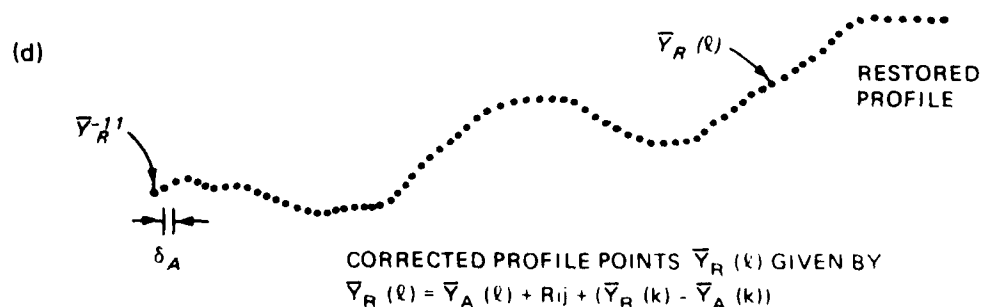
Equation (A-14) is derived from Equation (A-10) by substituting into the latter two successive values of i and by subtracting the resulting expressions.

(a)

ACTUAL PROFILE

(b)

SYM POINTS

$\bar{Y}_S (i)$

$\bar{Y}_S (3)$

$\bar{Y}_S (j-1)$

$(\bar{Y}_S (j) - \bar{Y}_S (j-1)$

$\bar{Y}_S (2)$

$\bar{Y}_S (1)$

δ_S

(c)

$\bar{Y}_A (1)$

$\bar{Y}_A (\ell)$

ASY POINTS AFTER 20m CUTOFF FILTER

$\bar{Y}_A (1)$

$\bar{Y}_A (2)$

$\bar{Y}_A (j-1)$

$\bar{Y}_A (j)$

$\bar{Y}_A (3)$

$(\bar{Y}_A (j) - \bar{Y}_A (j-1)$

δ_A

CORRECTION (R_{ij}) TO BE ADDED TO FILTERED ASY POINTS $\bar{Y}_A (\ell)$ IN THE RESTORATION PROCESS OVER STEP LENGTHS δ_S BETWEEN ASY PROFILE POINT AVERAGES $\bar{Y}_A (j-1)$ AND $\bar{Y}_A (j)$ IS GIVEN BY:

$$R_{ij} = [(\bar{Y}_S (j) - \bar{Y}_S (j-1)) - (\bar{\bar{Y}}_A (j) - \bar{\bar{Y}}_A (j-1))] \; \delta_A / \delta_S \qquad \text{FOR } i = 1,2 ... \delta_S / \delta_A$$

$$\text{WHERE } Y_A (j) = \sum_{m = (j-1) \delta_S/\delta_A + 1}^{j \delta_S/\delta_A} \frac{\bar{Y}_A (m)}{\delta_S/\delta_A}$$

(d)

$\bar{Y}_R (\ell)$

RESTORED PROFILE

$\bar{Y}_R 1'$

δ_A

CORRECTED PROFILE POINTS $\bar{Y}_R (\ell)$ GIVEN BY

$$\bar{Y}_R (\ell) = \bar{Y}_A (\ell) + R_{ij} + (\bar{Y}_R (k) - \bar{Y}_A (k))$$

WHERE

$$\ell = i + (j - 3/2) \; \delta_S / \delta_A \qquad i = 1,2 ... \delta_S / \delta_A$$

$$k = (j - 3/2) \; \delta_S / \delta_A$$

$\left. \right\}$ $j = 2,3 ...$ ETC.

Figure A-5. Reshaping of Filtered ASY Profile to Restore Long-Wave Features Measured by SYM System.

D. AMPLITUDE AND PHASE RESPONSE OF THE PROFILOMETER

Because profiles measured by the profilometer system are defined at discrete points spaced at a distance δ_A apart, strictly accurate amplitude and phase response of the system cannot be determined. However, approximate response curves for phase and amplitude can be defined, as shown in Figure A-6, where it is assumed that there are no errors in the measurement process.

The amplitude response curve in Figure A-6 shows the attenuation of the short-wave features of the profile caused by the averaging process adopted in the ASY profile measurements described above. The phase-response curve in Figure A-6 shows that, if there are no measurement errors, there is no phase distortion in the profile measured by the profilometer except in the region of 2-meter wavelengths where about 5 degrees of phase shift is introduced by the filter described above. In practice, small measurement errors are caused by surface texture, beam curvature, imprecise calibration of the displacement transducers, and inaccurate distance measurements. The influence of these errors on the amplitude and phase response of the profilometer is discussed in the following section.
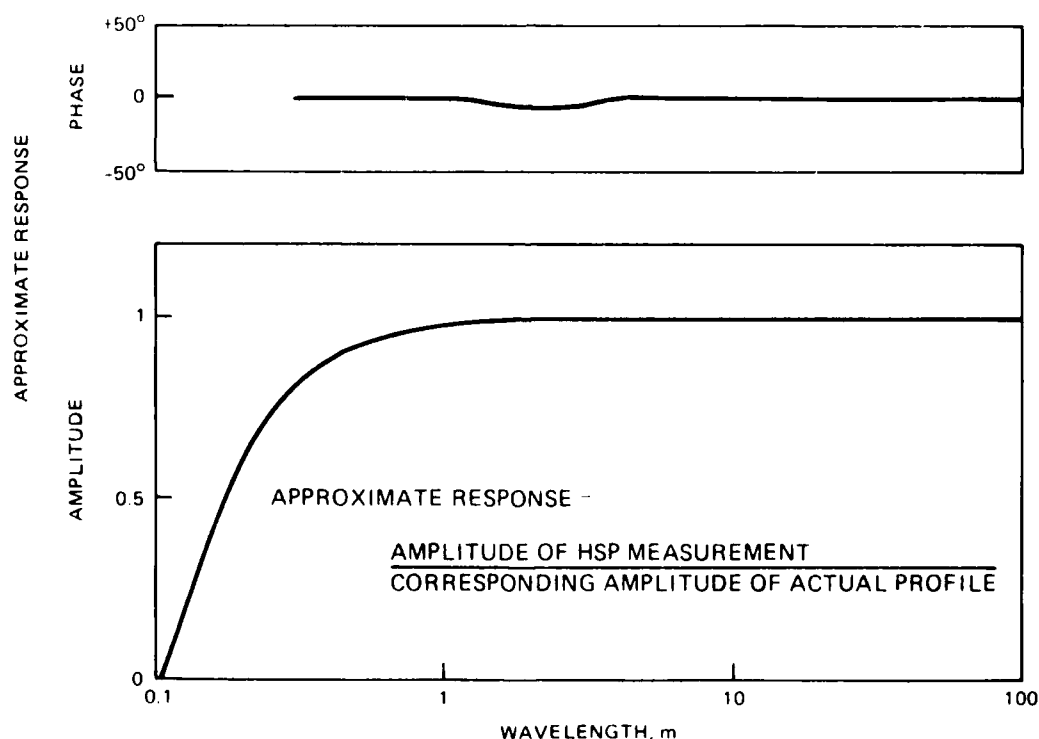
Figure A-6. Approximate Response of Profilometer, Assuming No Errors in Measurement.

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E. MEASUREMENT ERRORS

As described above, the profilometer transducers measure the average height of the profilometer beam above the textured surface over step lengths of δ_A for the ASY system and δ_S for the SYM system. Although the averaging reduces the magnitude of the texture effect, small residual errors remain in the averaged height measurements. The size of these residual errors depend upon the texture depth and on the number of actual displacement measurements made by the transducers over each step length.

A simple error model for the displacement measurements is given by:

$$h_i = h_i^0 + t_i + q(j-1)_i \qquad \text{(A-15)}$$

where

h_i = actual displacement measured by a transducer at the ith point

point

h_i^0 = true displacement at ith point

t_i = texture contribution at ith point

$q(j-1)$ = transducer resolution error where q is a constant and j is one of 0, 1, or 2 and is randomly selected at the ith point

Using this model, the error $\sigma(\bar{U}_o - \bar{U})$ caused by texture in the Calculation of the characteristic measurement of the SYM profiling system over a step length δ_S is given by:

$$\sigma(\bar{U}_o - \bar{U}) = \sqrt{\frac{6V}{\delta_S F(1 - P)}} \left[\sigma(t)\right] \qquad \text{(A-16)}$$

The symbols V , δ_S , F, and P represent the profilometer speed (m/sec), the SYM step length (meter) , the sampling frequency of the transducers and the proportion of dropouts (lost displacement measurements), respectively. The root-mean-square texture depth* is given by $\sigma(t)$. For the SYM system, F and δ_S are fixed and Equation (A-16) shows that as $\sigma(t)$, V , and P increase so also does $(\bar{U}_o - \bar{U})$.

The errors in the calculated SYM profile accumulate with each succeeding profile point, and the effect of this cumulative error is to cause the calculated profile to wander relative to the true profile. The variability $\sigma(d)$ of the deviations between any given point n on the calculated profile and the corresponding point on the true profile can be obtained using Equations (A-3) and (A-16) and is given by:

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* The root-mean-square texture depth is obtained from displacement measurements by a single transducer of the profilometer; the root-mean-square calculation is carried out on the profilometer's computer.

$$\sigma(d_n) = \sigma(\bar{U}_o - \bar{U}) \sqrt{\sum_{i=1}^{n} i^2} = \sigma(\bar{U}_o - \bar{U}) \sqrt{\frac{(2n^3 + 3n^2 + n)}{6}} \quad . \quad \text{(A-17)}$$

If texture depth and the operating conditions of the profilometer are assumed to remain constant during the measurement, $\sigma(\bar{U}_o - \bar{U})$ will be constant. Although Equation (A-17) shows the variability of the deviation at point n to increase as $n^{3/2}$, it does not indicate the trend of the deviations along the profile length.

If this trend is oscillatory, with a wavelength comparable to the actual wavelengths that are being measured, then significant distortion of these profile features could result. If, however, the trend is linear or approximately linear over lengths comparable to the profile wavelengths of interest, then the distortion would be considerably less.

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