DATA ACQUISITION SYSTEMS FOR THREE-DIMENSIONAL REPRESENTATION AND ANALYSIS OF SURFACE TOPOGRAPHY AND SURFACE TEMPERATURES IN TRIBOLOGICAL PROCESSES

by

Jayaram Sankar

Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Mechanical Engineering

APPROVED:

Michael J. Furey, Chairman

Arvid Myklebust

Henry L. Wood

Norman S. Eiss (Jr)

May 1986

Blacksburg, Virginia

DATA ACQUISITION SYSTEMS FOR THREE-DIMENSIONAL REPRESENTATION AND ANALYSIS OF SURFACE TOPOGRAPHY AND SURFACE TEMPERATURES IN TRIBOLOGICAL PROCESSES

by

Jayaram Sankar

Michael J. Furey, Chairman

Mechanical Engineering

(ABSTRACT)

Data acquisition systems were developed for three-dimensional representation and analysis of surface topography and surface temperatures in tribological processes. 3-D information about the topography of surfaces was obtained from parallel traverses of the stylus of a Talysurf 4 profile-meter. MOVIE.BYU and Tektronix graphics terminals were used to display the models of the surfaces.

Surface temperatures generated by friction were measured using a Barnes RM-2A Infrared Radiometric Microscope. The sliding system consisted of a pin (or sphere)-on-disc mechanism. An optically flat, transparent sapphire disc was used as the rotating member.

A computerized data acquisition system (consisting of an IBM PC and a Data Translation 2805 I/O system) was interfaced with the IR microscope and its accessories to help scan the region of contact and record data to generate maps of the radiance distribution over the scan-area. MOVIE.BYU and Tektronix graphics terminals were used to display the radiance maps in three dimensions. A method for studying fast thermal transients in the sliding system is suggested and demonstrated. This method uses the unfiltered signal from the IR microscope to detect the transients.

Some simple tests were conducted to observe the general performance of the systems mentioned above. The test results along with suggestions for possible areas of improvement are discussed.

ACKNOWLEDGEMENT

Table of Contents

List of Illustrations

1. Introduction

Tribology--the study of friction, wear and lubrication--is an important element of engineering. Tribology is an important factor not only in the conservation of materials and energy but also in the welfare and safety of human beings. The proper application of lubrication science and technology can lead to considerable savings in maintenance and replacement costs as well as savings in losses which result from breakdown or premature failure. Although a great deal of work has been done in trying to understand tribological processes, there is still a lack of detailed knowledge of the various phenomena in such systems (e.g., the actual area of contact in a solid-solid interface, the frequency of contact, surface temperatures produced by friction, etc.).

One of the most important unknowns in tribology is the temperature of rubbing surfaces. Surface temperature affects both the physical and the chemical properties of the interacting surfaces and also of the media between the two solids. Physical properties affected by temperature include, for example, hardness and elasticity of the rubbing bodies; chemical changes brought about by temperature variations may include oxidation or lubricant deterioration. Gear scuffing and frictional heating of strips and wires during drawing are some practical examples of effects of heat generated by friction.

However, it would be incorrect to assume that heat generated by friction is always an undesired effect. The high temperatures produced by sliding friction have been successfully harnessed and used in production welding. Furey [1] has shown that certain metallic dithiophosphates function as anti-wear additives because they are thermally unstable. His concept of "in situ" polymer film formation as an antiwear mechanism [2] is also based on the surface temperatures produced at sliding interfaces. According to this theory, the potential polymer forming compound is mixed at low concentrations in a carrier. Due to high surface temperatures in the regions of greatest contact and possibly the added catalytic action of freshly exposed surfaces, very thin protective polymeric films form in these areas. Although many theories have tried to predict the surface temperatures of rubbing bodies, there is very little experimental data to verify these theories.

Another important unknown in tribological systems--one related to the above--is the actual area of contact between rubbing bodies. This actual area of contact is influenced by the topographies of the two contacting surfaces. In recent years, there has been a considerable improvement in the understanding of the influence of surface topography on the tribological performance of metals and non-metals. There have also been remarkable advances in the ability of the engineer and the scientist to measure and describe the shape of surfaces. Nevertheless, there is still some confusion as to which textural features of a surface are critical and which are irrelevant in the study of friction, wear, and lubrication of metals and/or non-metals in contact with each other.

At present, in the study of solid surfaces, theoreticians are developing numerical descriptions of surfaces and theories of surface interaction. Some investigators are exploring the mechanisms of surface interaction and are trying to determine which aspects of their texture are relevant in practical applications. Although various methods have

been used to physically characterize rough surfaces, very few of these have been able to produce accurate maps of the surfaces. Most of the roughness measurements end in numbers, for example, center line average, bearing area, maximum peak to valley height, etc. [3] . An important aspect, which is frequently missed, is the fact that some surfaces may be characterized by the same numbers, but may look different and behave differently. Thus, it becomes quite clear that many fundamental problems associated with surface roughness require quantitative information about the surface in three dimensions to produce accurate and realistic maps of the surface.

In each of the areas mentioned above, the systems are complex and dynamic, and experimental measurements are extremely difficult. However, recent advances in data acquisition systems and computers open the door to improved methods in the acquisition and analyses of tribological data. Thus, the thrust of this study is to develop and apply a computerized data acquisition system to increase the understanding of the basic phenomena occuring in tribological processes.

2. Rationale and Objectives of this Study

During the past several years, a sophisticated system for measuring surface temperatures generated by friction has been developed in the Tribology Laboratory at VPI & SU (a discussion of what the system is capable of measuring, types of previous studies, and possible sources of error was presented by Furey at Eurotrib 81 held in Warsaw [4]). Although the system had been gradually improved over the years, it was thought that new techniques were needed in the acquisition, handling, and analysis of data--particularly the radiance data.

In the previous system--the one used by Omori [5], Richardson [6], Li [7], Rogers [8] and Moyer [9]--radiance was measured using the so called "DC" mode of the Infrared Radiometric microscope, with the data being recorded on an FM tape recorder and played back at a slower speed on a chart recorder with 12 inch paper. Although the results were useful--representing valuable and fundamental experiments which had never been carried out before--some difficulties arose. In addition, it became obvious that all the information was not being extracted from the data. Some examples are :

1. Reading of radiance data was done by eye from the chart--with "averages" and ranges of maximum and minimum being determined by drawing straight lines on the chart.

2. Because of these difficulties, no attempts were made to correlate changes in radiance with changes in friction.

3. Some "mapping" of the radiance levels within the contact region during sliding was tried (e.g. by Richardson [6] in his work with graphite) but this was a very time-consuming and difficult procedure since values of X and Y positions read from the FM tape had to be manually picked off and cross-plotted against radiance.

4. Although the Barnes IR instrument was capable of making radiance measurements either in a "DC" mode (0 to 400 Hz) or an "AC" mode, no one had ever used the latter. This information on transient and peak surface temperatures was not obtained. In the interim, Dr. Henry L. Wood, Professor of Mechanical Engineering at VPI & SU, modified the circuit so that the DC and the AC modes could be used simultaneously. But it had not been used or evaluated.

5. The problem of transfer of material to the rotating sapphire disc was always of concern since any transferred material could attenuate the IR signal and thus reduce the radiance detected by the microscope. It was thought that an advanced data acquisition system could show the radiance in one revolution of the disc (no transfer), two revolutions, ten revolutions and so on. This would allow the user to detect any effects of transfer films.

6. It was also felt that a detailed frequency analysis of the radiance data--either in the DC-400 Hz or the AC mode--would provide valuable, unique, and fundamental information on surface temperatures in the contact zone at a given point.

7. Rogers [8] developed a very accurate method for the conversion of the microscope output voltages radiance and then to temperature. This method was very successful in converting radiance data to surface temperatures. But, the transformation of

complex radiance data to surface temperatures by the use of emissivity, calibration factors, and instrument constants was a tedious and time-consuming process.

8. In addition, it was felt that some of the variations in radiance and surface temperature over a macroscopic region of contact could be attributed to the actual areas in contact. This, in fact, was demonstrated by Richardson [6] who used both radiance mapping and scanning electron microscopy on worn graphite specimens. It is conceivable that radiance maps of a complex contact region could provide basic information on the actual areas in contact--another important unknown in tribology. Thus, it might be possible to examine surface topography of test specimens before and after surface temperature experiments using an advanced system in which a Talysurf profile instrument could be connected to a computer and 3-D modeling software to generate models of the surface. In fact, the mapping techniques used for IR measurement could also be used for surface topography measurements. Although the Talysurf had been used in the past with a computer for extracting statistical data, no attempts were made to model such surfaces using 3-D solid modeling techniques.

9. Last, it became obvious that with the recent and rapid developments in data acquistion systems, computers, computer graphics, 3-D modeling techniques, and signal analysis techniques, the time was ripe for an intensive, coordinated effort to develop and apply these techniques to such tribological measurements. Although the central thrust of this system would be aimed at the IR system for measuring surface temperatures, it would also be useful not only in surface topography but in any measurements (e.g., friction, wear, fretting, etc.) carried out in the Tribology Laboratory.

Thus, the goals of this study were as follows :

1. To develop computerized data acquisition systems to :

   a. Generate 3-D maps of rough surfaces using computer graphics.

   b. Digitize and record information from the infrared microscope system.

2. To generate surface maps of some typical surfaces using the system mentioned above.

3. To carry out some simple experiments with sliding systems and :

   a. Generate maps of surface temperature distribution over the region of contact.

   b. Record fast thermal transients.

4. To demonstrate the use of the digital system in performing statistical analyses and other treatments of the data (e.g., conversion of radiance data to temperature).

This thesis will discuss :

1. The development of the computerized data acquisition systems--the approach used, description of the systems, and characteristics of the systems.

2. Application of one system to the study of surface topography; examples of results and data obtained.

3. Application of the second to the study of surface temperatures; examples of data obtained.

4. Advantages and limitations of the data acquisition systems; comparison with previous techniques.

This work centered on two major and important areas in tribology--surface temperature measurements from the IR system developed at VPI & SU and surface topography measurements using a Talysurf 4 profile-meter. These areas are important and also connected. For example, surface topography influences the nature and area of contact in tribological systems, and the area of contact is an important factor in influencing the surface temperatures produced by friction. Since the measurement of surface topography is simpler than that of infrared radiation from a dynamic system, the study presented here began with surface topography measurements.

As a brief background, the next section discusses some of the major experimental approaches which have been used in measuring surface topography and surface temperatures in tribological systems, particularly as they relate to the present study. This is not an exhaustive review, but just a brief survey of the various techniques used.

3. Literature Review

3.1 A Brief Survey of Surface Mapping Techniques

There are many different ways of measuring surface roughness and mapping surface profiles (e.g., optical techniques, electron microscopy, scanning electron microscopy, stylus techniques, etc.). The selection of a system for characterizing surfaces depends on the individual application. A discussion of various mapping techniques, along with their advantages and shortcomings, has been provided by Thomas [10].

The instrument most commonly used to map surfaces is the stylus-type profile meter. The earliest stylus instruments amplified the vertical movement of the stylus mechanically by a system of levers. Modern stylus instruments use a transducer to convert the vertical movements into electrical signals. Such instruments on their own, however, are not capable of providing information about the surface in three dimensions and hence various ingenious techniques have been designed by investigators for this purpose.

Since the stylus instrument is the most widely-used method for roughness measurements, it is not surprising that many investigators have tried to develop mapping techniques based on this instrument. The stylus usually traces out a line; hence, some kind of scanning technique is required to get information in three dimensions. Guerrero and Black [11] have discussed stylus tracer resolution and surface damage as determined by a Scanning Electron Microscope.

Edmonds [12] has described the development of a 3-D relocation table which interfaces with a Talysurf 4 profile meter to enable a polar scan of the surface. This set-up was capable of accurate relocations but there were no proper data recording or visualizing techniques. McAdams et al. [13] developed a computer method for regenerating an abrasive surface from a finite number of elevations (relative to a reference plane) obtained from a stylus instrument. This method employs vector-space theory to develop an equation of the surface in terms of locally defined "patches". The sample points were 0.005 in. apart (in both the X and Y directions) and the final results of this method were shown on a plan view contour map with contours at selected elevation levels. The elevations were thresholded at 0.005 in. intervals and the output device was a line printer.

Wallach [14] has presented a numerical method for the description of surface topography. In this method, an unknown surface is analyzed by recording parallel traces of surface heights using the stylus method. The measurements were made with a Talysurf instrument with the parallel traces spaced 1 mil apart and each trace referenced to the optical flat in the Talysurf head. The sample was moved by a micrometer stage and each trace was sampled every 0.32 mil. The two-dimensional distribution of surface heights was Fourier-analyzed for waviness. The waviness was subtracted out and the remaining roughness numerically analyzed to determine the probability distribution. The result was a numerical description of the surface topography. Although this method

was capable of obtaining information about the surface in three dimensions, the data were not used to generate any maps of the surface profile.

Grieve et al. [15] used a Talysurf III stylus instrument interfaced with a digital computer to measure changes in surface topography that occur during wear. Close parallel traces, spaced 7.5 microns to 15 microns apart, were made with the stylus to obtain a 3-D representation of the surface. The recorded profiles were fed to the computer and then printed out as an array of spot heights from which contour maps were produced. Directional surface effects were examined by evaluating parameters describing the slopes in different directions. An Oscillating stylus was used by Deutch et al. [16] to measure and record irregular surfaces; the resultant data was fed into a computer to generate contour maps.

In 1975, Sayles and Thomas [17] developed an automated system for mapping, measuring, and analyzing small areas of surfaces. In this system, a Talysurf 3 stylus instrument was fitted with an automatic stylus return mechanism and a traversing device to position the specimen relative to the stylus prior to each traverse. The distance between parallel traverses was 4 microns and each trace was sampled at intervals of 1.6 to 8 microns. The data was loaded on to an ICL 1905E computer. A program was used to take a series of parallel traces and plot each one slightly displaced horizontally and vertically from the previous one. Each profile was smoothed with cubic splines before plotting. To prevent any crossover of profiles, a dummy profile was carried in the core and compared with each real profile in order to remove hidden lines. After each line was drawn, the dummy profile was updated for comparison with the next profile. This method of plotting was able to generate isometric views of the surface. Although pictorial information was extracted, the main purpose of this system was to extract statistical information.

A non-contact Optical Profilometer, working on a raster scan principle for obtaining spatial characterization of three-dimensional surfaces, has been described by Kelly [18]. In this method, photo detectors observed the change in the energy distribution of an image spot of light as a function of the depth of the sample surface at the measurement point. The sample surface was scanned to provide roughness information over the entire surface. The vertical resolution of this instrument was reported to be only 50 microns and its use was limited to sample surfaces with a uniform reflectance or which could be temporarily coated. The storage and computational capabilities of this system were very limited and although three-dimensional information was generated, the viewing techniques were very poor.

Wyant et al. [19] designed a three-dimensional Non Contact Digital Optical Profiler for measuring surface roughness. A coherent beam of light (wavelength of 650 nm) from a tungsten halogen bulb was directed at the surface. Interferometric phase shifting techniques were used to obtain surface height information from the light reflected by the surface. The height measurements were processed by a computer to obtain topographical statistical parameters. The interference fringes illuminated a 384 x 244 pixel charge injection device (CID) image sensor. The total area being measured was 0.50 x 0.50 mm (with a 10X objective) or 0.28 x 0.28 mm (with a 20 X objective). Some examples of 3-D plots of the surface and plots of statistical data were also presented.

In the work presented in this thesis, a Talysurf 4 stylus profile meter was used to make parallel traces and generate three-dimensional polygonal models of the surface. This system is different from the mapping techniques discussed above because the models generated are three-dimensional models and not just two-dimensional isometric views. Moreover, the geometry is stored in the computer in a form which can be easily

read by many of the commonly-used engineering analysis and graphics packages (e.g., MOVIE.BYU, I-DEAS etc.).

3.2 A Brief Survey of Experimental Techniques in Surface Temperature Measurement

. Several methods have been used to measure surface temperatures generated by friction. These include the use of embedded thermocouples, the 'dynamic' thermocouple, thin film transducers, recording of visible hot spots, evidence of metallurgical phenomena (e.g., melting, changes in microstructure), contact thermocouples, and infra-red techniques (e.g., pyrometers, thermography, and photon detectors). An excellent review of the mechanisms of frictional heating and the measurement and analysis of surface and near surface temperatures resulting from such heating has been presented recently by Kennedy [20] . According to him the three most commonly-used methods are the embedded thermocouple, the dynamic thermocouple, and the IR technique.

The embedded thermocouple method is a very poor one for estimating surface temperatures. A major drawback of this method is that the thermocouple should be very close to the surface to give an approximation of the surface temperature. But, the closer the thermocouple is to the actual rubbing interface, the more likely it is to interfere with the flow of heat from the interface. Embedded thermocouples are more useful in measuring bulk temperatures within the sliding bodies than in measuring the contact temperatures.

In the "dynamic" thermocouple method, the contacting bodies themselves, or portions of them, act to create a thermocouple junction at the sliding interface. Furey [21] has discussed attempts by various scientists at using the dynamic thermocouple

13

method for determining surface temperatures. He applied this method to a ball-on-cylinder system using a constantan ball on a steel cylinder. Time-averaged as well as instantaneous surface temperatures were determined. These results were compared with theoretically predicted values. The experimentally obtained temperatures were much lower than the theoretically predicted mean temperatures. Possible reasons for this difference and some advantages and disadvantages of the dynamic thermocouple method are also discussed in the paper.

In the same study [21], Furey made some measurements with thermocouples embedded in the constantan ball close to the contact area. It was found that the internal temperatures (indicated by the embedded thermocouple) were always more nearly constant with time than the surface temperature (indicated by the dynamic thermocouple). The temperature indicated by the embedded thermocouple was much lower than that indicated by the dynamic thermocouple even when the wear on the ball was great enough to reach the embedded thermocouple. This conclusively demonstrated the futility of using embedded thermocouples to measure surface temperatures.

The method of infrared detection involves the detection and measurement of the infrared radiation from the interface. In order to be able to detect this radiation, one of the rubbing surfaces must be transparent to the infrared radiation in order to enable the detector to "see" the interface. This, of course, restricts the variety of material pairs available for study. But this technique allows the user to measure surface temperatures without interfering with the flow of heat.

Bowden and Thomas [22] were one of the first to use the IR detection technique to study surface temperatures. They used a lead sulphide cell to observe the friction generated temperatures. This infrared detector had a time constant of about 10^{-4} secs at

$20^\circ C$ and was used to study various sliding systems--metals and non-metals on a rotating glass disc. This investigation had limitations however; the infrared transmissivity of glass is relatively low, the target area was not given, and friction was not measured.

In 1958, Reichenbach [23] used a lead sulphide infrared detector to measure metal cutting temperatures. The cell "looked" through a small hole drilled in the work material and sensed the radiation from the shear plane and the clearance face of the tool. Although peak temperatures in these regions were obtained, shear plane temperature distributions could not be determined successfully. Chao et al [24] also used a lead sulphide detector to measure surface temperatures in metal cutting. In their experiment, the detector "looked" at the tool flank immediately after contact--i.e., the flank surface was momentarily exposed to a cold surrounding before it could be seen by the cell. The output signal was displayed on a Cathode Ray Oscilloscope (CRO).

In 1971, Godet and Deyber [25] described an infrared technique for measuring the contact temperature in mixed friction, using a steel test block against a steel test ring, and a lead sulphide detector. Infrared detection was through a small sapphire window glued to a radial hole drilled in the test ring. The detector received radiation alternately from the test surface and a reference surface at a known temperature. In this system too, the detector "saw" the radiation shortly after the steel-on-steel contact. Moreover, the surface temperature had to be at least $30^\circ C$ above ambient temperature in order to be detected by the infrared cell.

In 1973, a detailed study was begun at VPI & SU, under the direction of M.J. Furey, to investigate surface temperatures in unlubricated systems of pure sliding. The apparatus was built around a Barnes RM-2A Infrared Radiometric Microscope and the sliding system consisted of a specimen loaded against a thin, rotating, sapphire disc. The

detector in the microscope was indium antimonide, cooled to liquid nitrogen temperature, with a response time of 8 microseconds. The target spot diameter (with a 36X objective) was 17.8 microns. This was the first instrument capable of measuring radiation from such a small area and thus brought up the possibility of mapping the temperature distribution over small regions of contact. A detailed description of this system along with an evaluation of its capabilities has been presented by Furey [1] and Wiggins [26]. This system was the basis on which the work presented in this thesis developed, and will be discussed in detail in the next chapter.

In 1973, Winer et al. [27] used an Infrared Radiometric Microscope to measure oil film and surface temperatures under elastohydrodynamic (EHD) lubrication conditions. The use of this system to determine the true temperature of a semi-transparent lubrication film of finite thickness is quite difficult since the detector "sees" a volume rather than a plane.

In 1974, Wymer et al. [28] used an Infrared Radiometric Microscope to measure gear tooth surface temperatures. The system consisted of a pair of lubricated spiral bevel gears mounted in a gearbox. The microscope had a 1/2 X reflecting objective with a target spot diameter of 1mm. The working distance of the lens was 0.5 m. The microscope detected radiation from the flanks of the 16 pinion teeth, a quarter of a revolution after contact. Evidence of a surface temperature jump during a "scoring-healing" cycle is also presented.

Ausherman et al. (1976) [29] and Nagaraj et al. (1977) [30] also used an Infrared Microdetector to study the effects of load, speed, and surface roughness on temperatures in a sliding EHD point contact. The contact geometry consisted of a rotating chrome steel ball loaded against a sapphire flat. The IR radiation emitted at the contact was

measured with a detector having a target spot size of 36 microns and a response time of 8 microseconds. Fluid temperature distribution (averaged through the thickness) was mapped over the region of contact.

4. Experimental

Two different experimental set-ups were developed in the course of this study--one for three-dimensional characterization of surfaces and one for measuring surface temperatures in a sliding system. The following are detailed discussions of these set-ups.

4.1 Surface Mapping

The experimental set-up used for the three-dimensional representation of rough surfaces consisted of a stylus type roughness measuring instrument (Talysurf 4 [31]) (Fig. 1), a Fast Fourier Transform machine (ZTL DMS 5003), a specimen mounted on a precision X-Y table, a host computer (IBM 4341) and a graphics terminal. A block diagram of the set-up is shown in Fig. 2.

The specimen was mounted on the precision X-Y table (Fig. 3) which in turn was mounted on the Talysurf 4 profile meter. The signals generated by the Talysurf were digitized by the FFT machine and sent to the digital computer. The data thus acquired
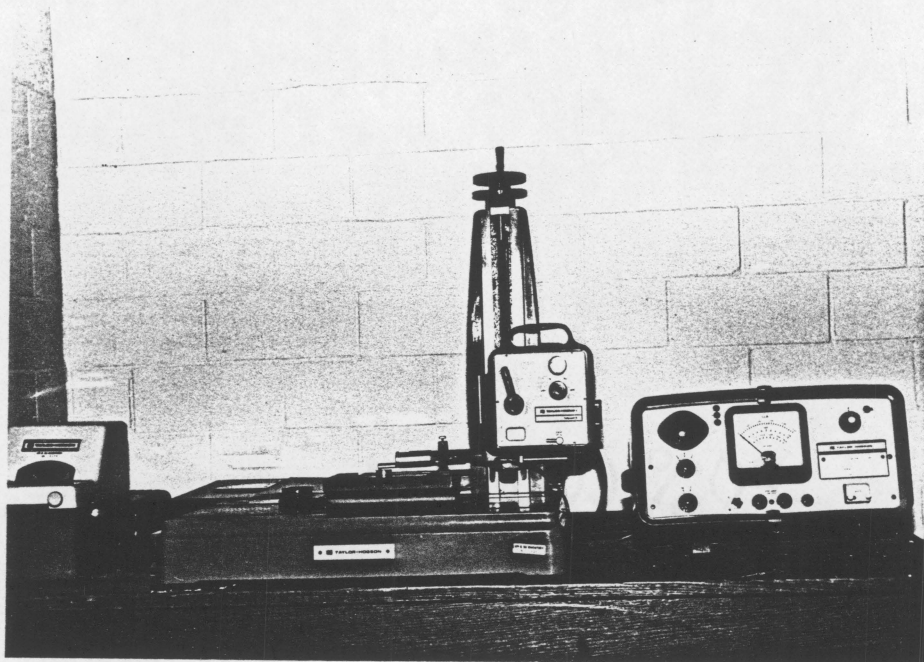
Figure 1. The Talysurf 4 Profile-Meter
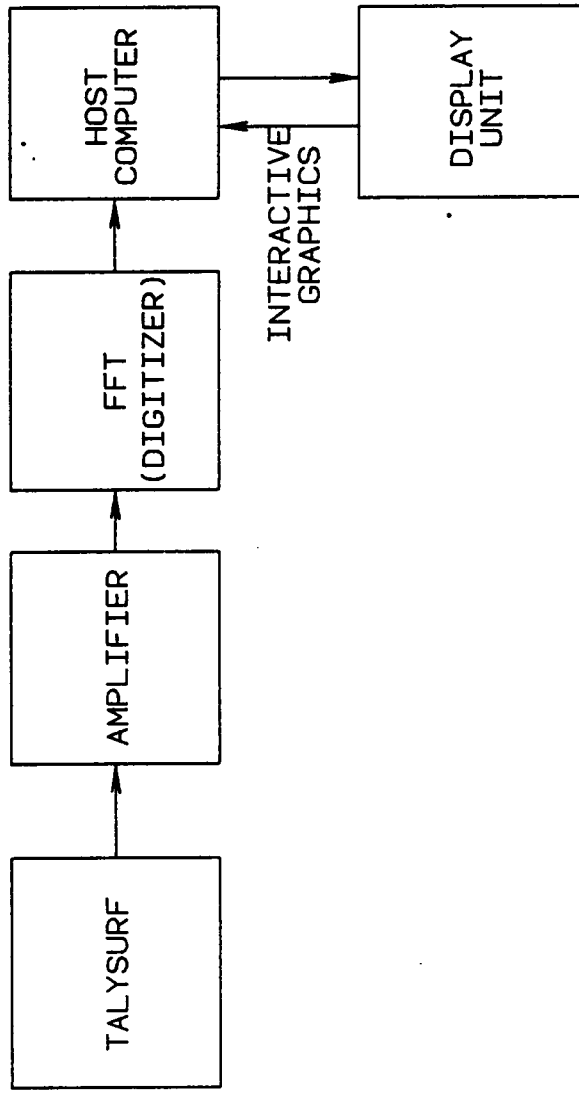
Figure 2. Set-Up for Surface Mapping

TAPE
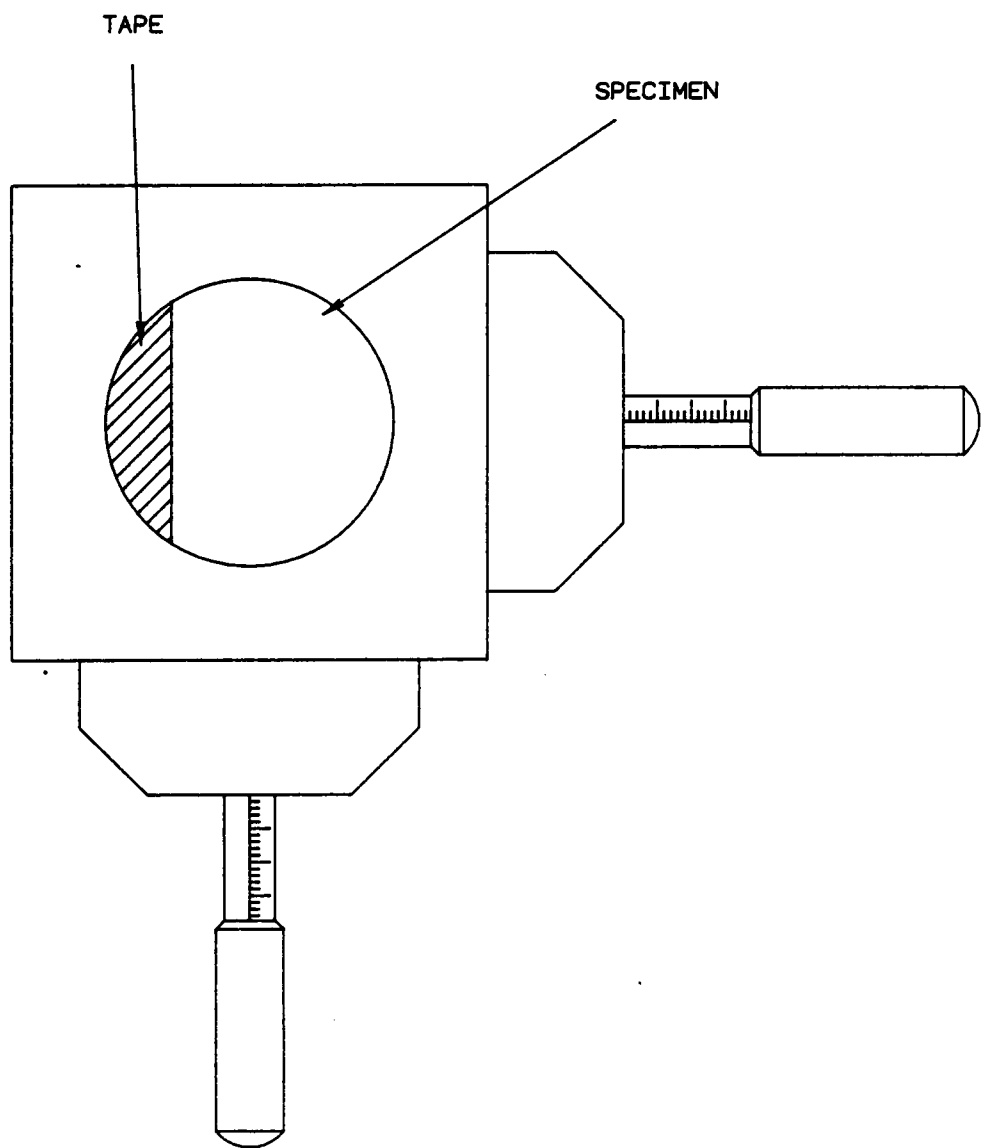
SPECIMEN

Figure 3. X-Y Precision Table

was processed by interactive FORTRAN programs on the IBM 4341 and then used by MOVIE.BYU (Appendix A) to generate 3-D models of the surface of the specimen.

Parallel traverses of the stylus were necessary to generate information about the surface in three dimensions. This was achieved by sticking a piece of adhesive tape on the specimen in such a way that the edge of the tape was perpendicular to the direction of traverse of the stylus of the profile meter. This perpendicularity was assured by using the cross-hair on the eyepiece of a microscope and positioning the specimen on the X-Y table such that the edge of the tape was parallel to one of the lines of the cross-hair.

The skid of the stylus was then positioned on the tape, while the stylus itself rested on the surface of the specimen (as shown in Fig. 4). The traverse was then started and the FFT triggerred itself when the skid jumped off the tape and produced a large jump in the signal from the Talysurf. The speed of the traverse and the sampling rate were adjusted such that the signal was sampled 1024 times during each traverse with the distance travelled by the stylus between two samples being 1.2 microns. After each traverse, the specimen was moved 6.35 microns (limited by the resolution of the X-Y table) in a direction parallel to the edge of the tape, with the help of the X-Y table; next, another traverse, parallel to the previous one, was obtained. The digitized data was then sent to the computer to generate the surface maps.

SKID

STYLUS

SPECIMEN

TAPE
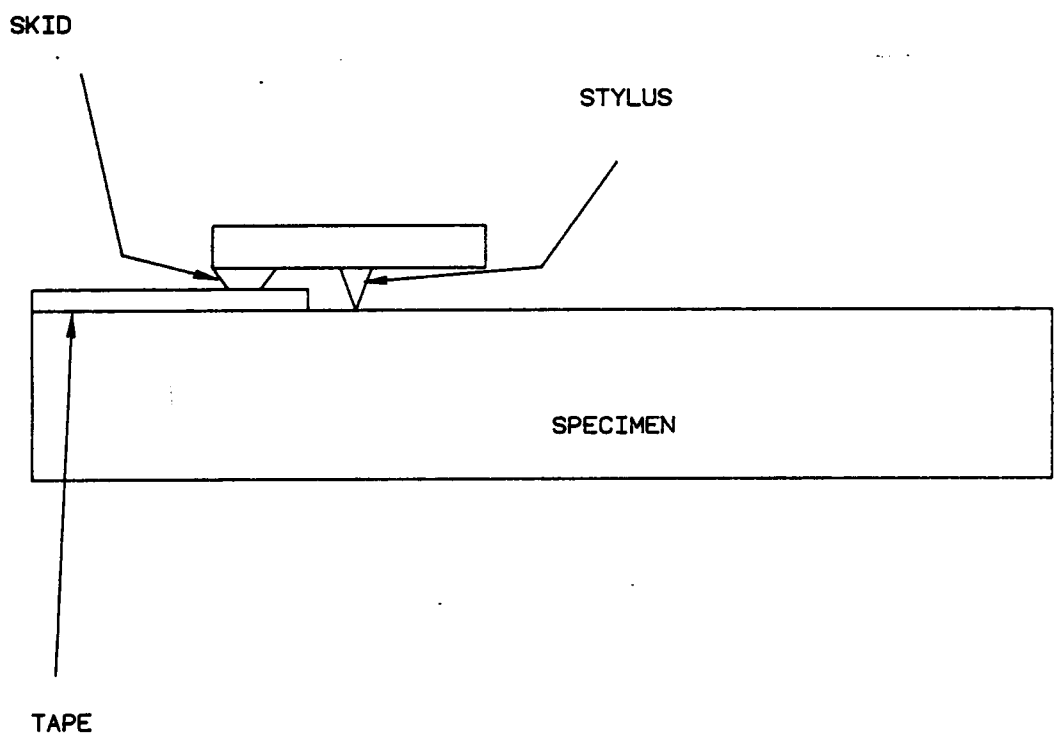
Figure 4. Specimen with Skid and Stylus

23

4.2 Surface Temperature Measurements

The experimental set-up used in this study of surface temperatures was first developed in 1973 and used over a number of years for a wide variety of studies. Furey [1] has summarized this program and discussed over 30 sources of possible error in this system. The following is a description of the system which existed at VPI & SU at the time this study began, and also of the data acquisition system which was developed and interfaced with it during the course of this study.

The system consisted basically of a fixed specimen loaded against a transparent, optically flat, rotating sapphire disc (50 mm or 25 mm dia. and 1 mm thick) (Fig. 5). Sapphire, because of its hardness, is particularly suitable for resisting wear and surface damage. The specimen is normally incapable of causing any abrasive wear of the sapphire. Moreover, sapphire is chemically inert for the purposes used in these studies. The disc was driven by a 1/6 HP, 3600 RPM hysteresis synchronous motor. This motor has low vibration characteristics and since the speed of the motor is proportional to the line frequency, the sliding speed remains constant. The rotational speed can be stepped down as low as 1 1/8 RPM or stepped up as high as 14,400 RPM by a system which includes a worm gear reducer, gear pulleys, and gear type timing belts (Fig. 6). This positive drive system ensured that no motion was lost due to slippage in the system. A magnetic pick-up, attached to the drive system, generated an electrical signal once every revolution of the shaft, and this signal was used to measure the RPM of the shaft.

The loading system, for loading the specimen against the disc, is shown in Fig. 7. This system consisted of a horizontal load arm, the test specimen, counterweights, a support yoke and a linear motion cross slide which enables the specimen to be located

BASIC CONTACT GEOMETRY

INFRARED
MICROSCOPE

REFLECTIVE
OBJECTIVE LENS

ROTATING
DISC

CONTACT
SPECIMEN

SHAFT

W
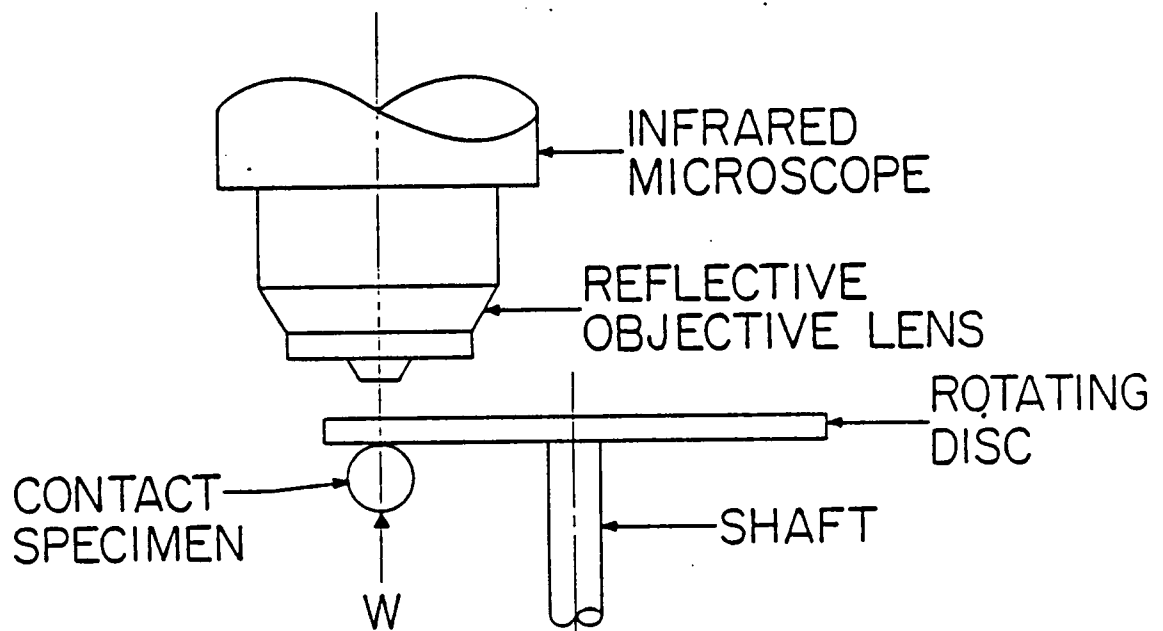
Figure 5. The Basic Contact Geometry (from Furey [1])
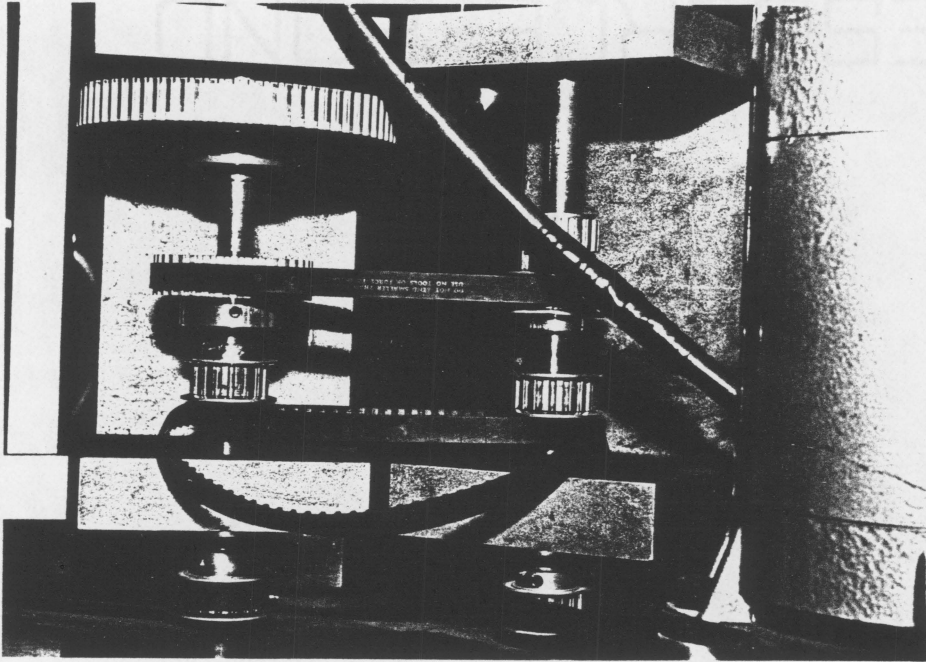
Figure 6. The Disc Drive System
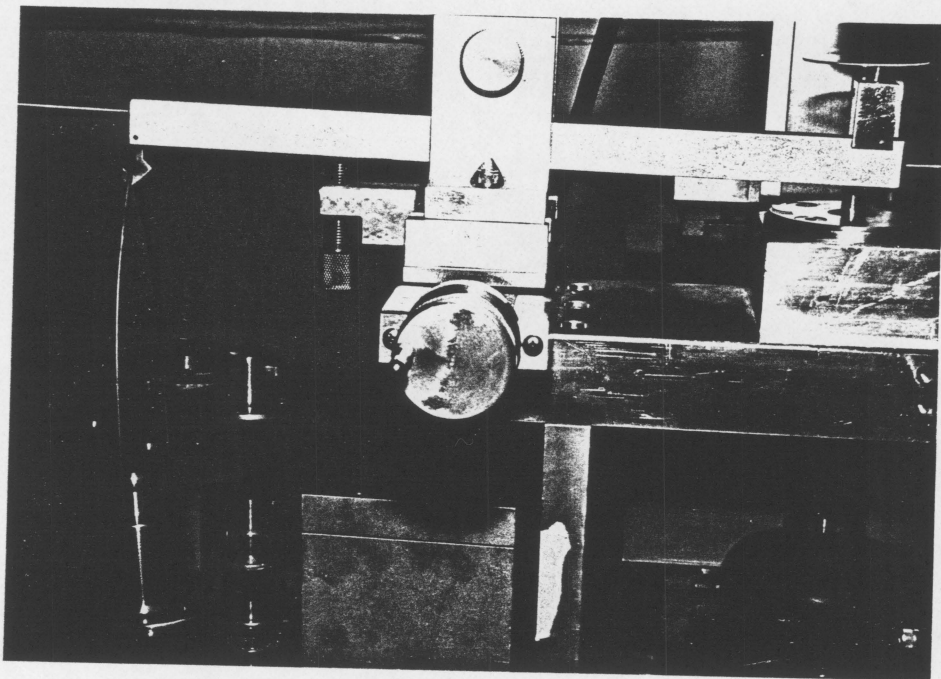
Figure 7. The Loading System

at various radii on the disc. Loads were applied by placing laboratory weights on the bowpan located on one end of the load arm. After counter-balancing, there was a 2:1 ratio between the load applied at the bowpan and the load exerted by the specimen; for example, a load of 2N on the bowpan produced a normal load of 1N between the specimen and the disc. This combination of the loading system and the disc drive system allowed loads from 0.1N to 10N, with sliding velocities ranging from 10^{-3} m/s to more than 10 m/s.

The friction force generated by the sliding interface was monitored by a rotary torque transducer (Fig. 8). This transducer measures the torque on the disc shaft and responds to torques ranging from 0.7 N-cm to 35 N-cm; it is capable of operating at speeds up to 20,000 RPM.

The heart of the temperature measurement system was a Barnes Infrared Radiometric Microscope (Model RM-2A) (Fig. 9). This microscope consists of a Microscope Unit and a Control Unit. The Microscope Unit allows viewing of the area of interest and simultaneously produces an electric signal proportional to the radiation emitted by that area. The Control Unit amplifies the signal from the Microscope Unit and makes it available at an output jack at the rear panel of the Unit. The Control Unit also produces direct temperature or radiance read outs [32] .

In the Microscope Unit (Fig. 10), the target radiation is collected and focussed by a Beck reflecting objective. The energy is then directed to a Germanium dichroic optical element which transmits the infra-red energy and reflects the visible energy to the eyepiece. The infrared energy transmitted by the dichroic element is incident on a tuning fork chopper, which is designed so that the target and reference radiations are alternately incident on the infrared detector. The chopper consists of the tuning fork chopper
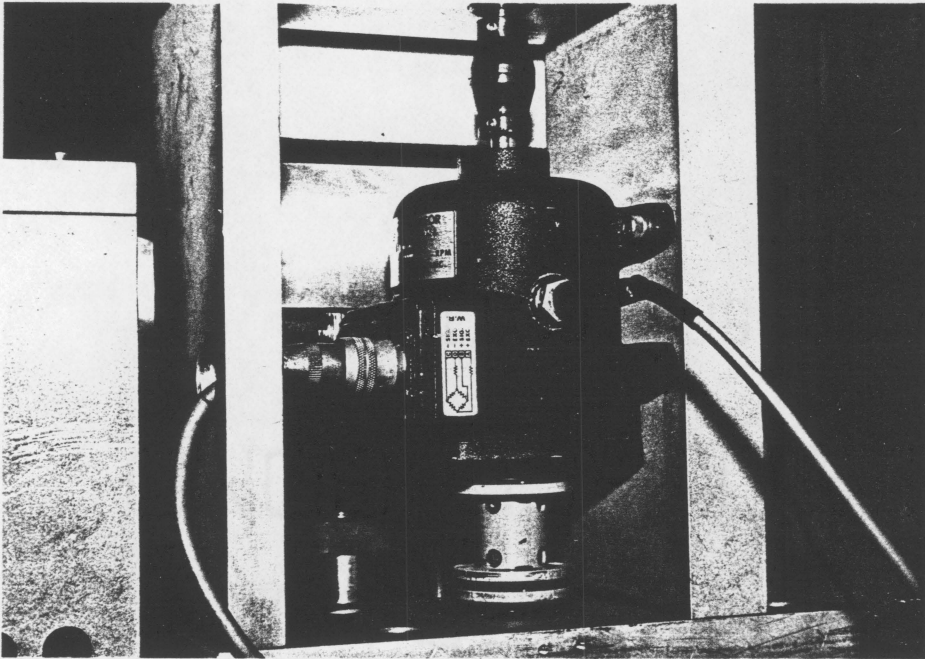
Figure 8. The Rotary Torque Transducer
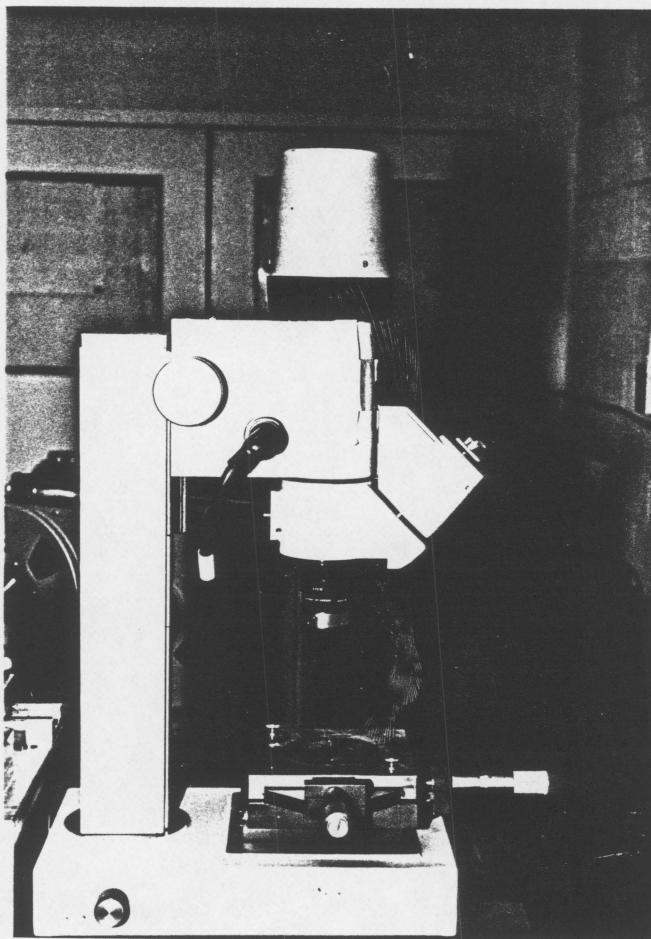
Figure 9. The Infrared Radiometric Microscope
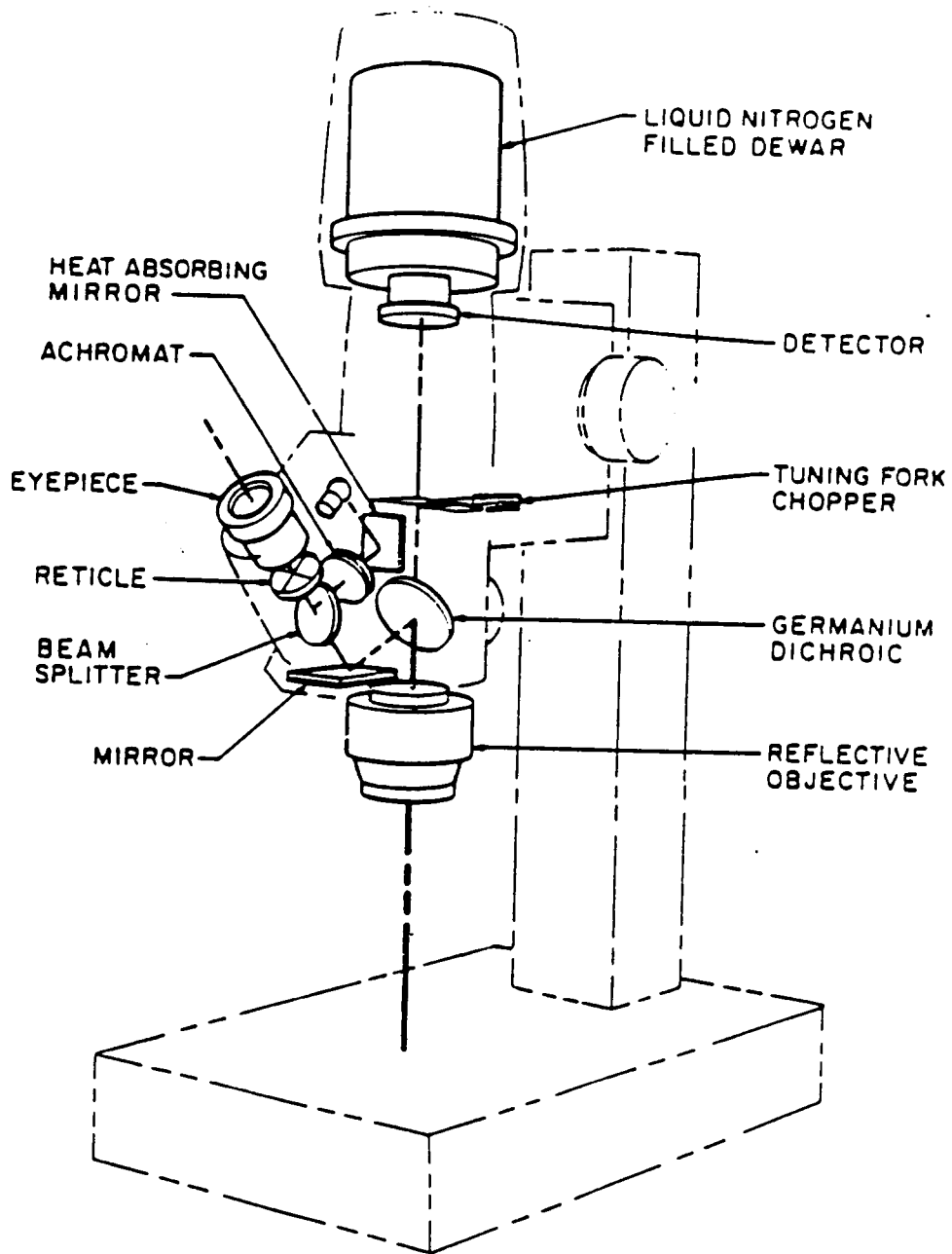
Figure 10. The Microscope Unit (from reference [32])

(which is vibrated at 600 Hz by a Function Generator in the Control Unit) with chopper blades attached to its tines. When the tines vibrate, the aperture alternately opens and closes. The frequency of chopping is twice that of the fork vibration. The chopping of the signal makes possible the use of an AC amplifier with high gain and stability.

An infra-red detector produces an AC output proportional to the difference in radiation observed during the open and closed intervals of the chopping cycle. The detector material is indium antimonide, mounted within a dewar flask for cooling to liquid nitrogen temperature. This cooling reduces noise generation in the detector. Indium antimonide detectors are characterized by very high sensitivity and rapid response (response time of less than 1 micro second) and respond to radiation between 1.8 and 5.5 microns. A pre-amplifier in the Microscope Unit amplifies the signal to a level suitable for transmission through a cable to the Control Unit.

The Control Unit is shown in a block diagram form in Fig. 11. It has two different modes of operation, determined by the position of an "AC-DC" switch at the rear panel of the unit. The AC mode is used to observe fast thermal transients (response time is about 8 microseconds), whereas the DC mode is used when continuous observation of the target is desired. In the DC mode, the signal from the Microscope Unit is fed first to a pair of feedback stabilized amplifiers (each having a gain of 22). The Emissivity Control is an attenuator, by means of which the amplifier gain may be increased to compensate for targets having emissivities less than 1.

In the Demodulator network, the 1200 Hz carrier frequency is removed by synchronous rectification techniques. After demodulation and filtering, a DC voltage is produced which is proportional to the difference between the target and reference radiations. In the Function Generator, an oscillator produces a 600 Hz square wave output

32
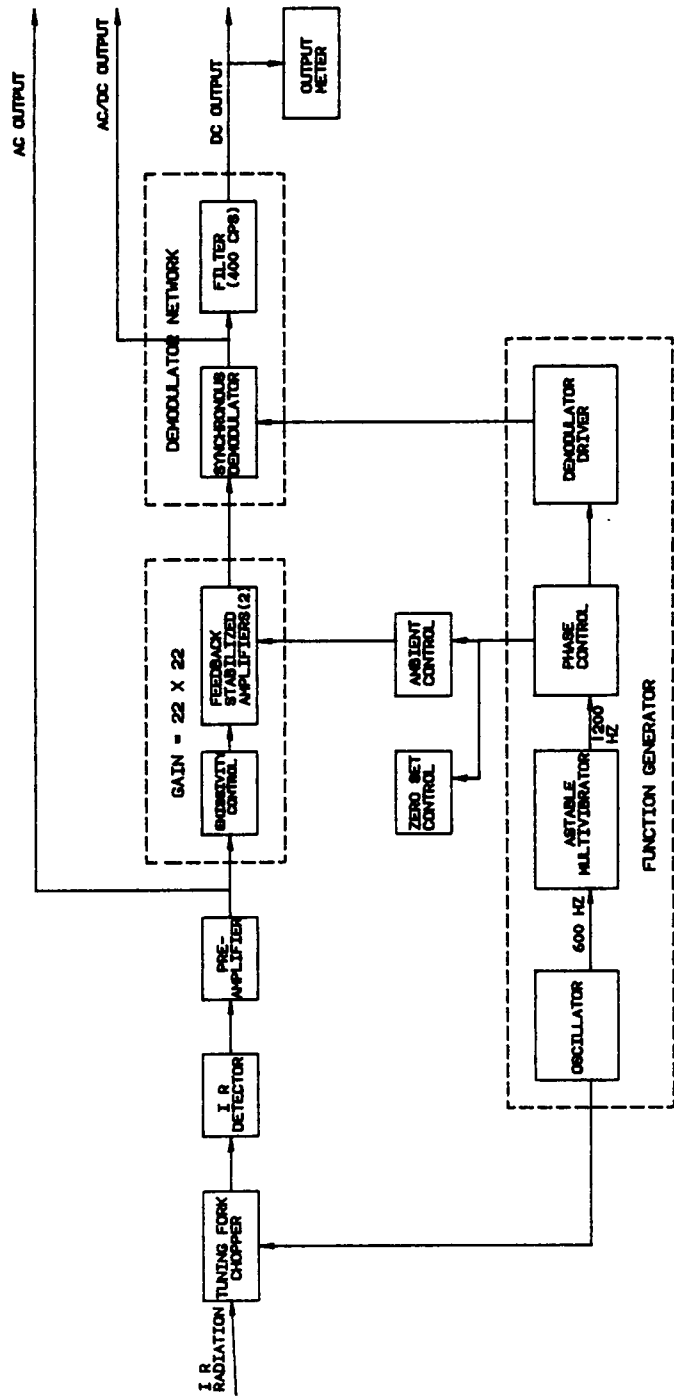
Figure 11. Block Diagram of the Control Unit

to drive the tuning fork chopper and an Astable Multivibrator. The Astable Multivibrator doubles the frequency generated by the oscillator to make the Demodulator, the Zero Set and the Ambient Control circuits compatible with the 1200 Hz chopper frequency.

In the AC mode, the chopper becomes inactive and the pre-amplifier signal is made available directly at the output jack. Dr. Henry L. Wood, Professor of Mechanical Engineering at VPI & SU, made some modifications to the Control Unit and added a second output jack to it. The signal to this output jack bypasses the low pass filter (the "AC/DC" output in Fig. 11). Thus, it became possible to study the signal from the microscope with the chopper operating and without any filtering, giving essentially an AC output superimposed on a DC output. This output was used in the experiments to study transient radiation.

The Microscope Unit was mounted on a precision X-Y table and could be positioned accurately, by turning two lead screws, anywhere over the surface of the disc. This flexibility allowed scanning of the small contact area in the x and y directions, thereby providing the capability to thermally "map" the region of interest. The exact position of the microscope was determined by the outputs from two LVDTs (Fig. 12).

A block diagram of the entire set-up involved in surface temperature measurements is shown in Fig. 13. The outputs from the two LVDTs, the microscope control unit, the torque transducer and the magnetic pick-up are fed into a computerized data acquisition system (described in the next section)
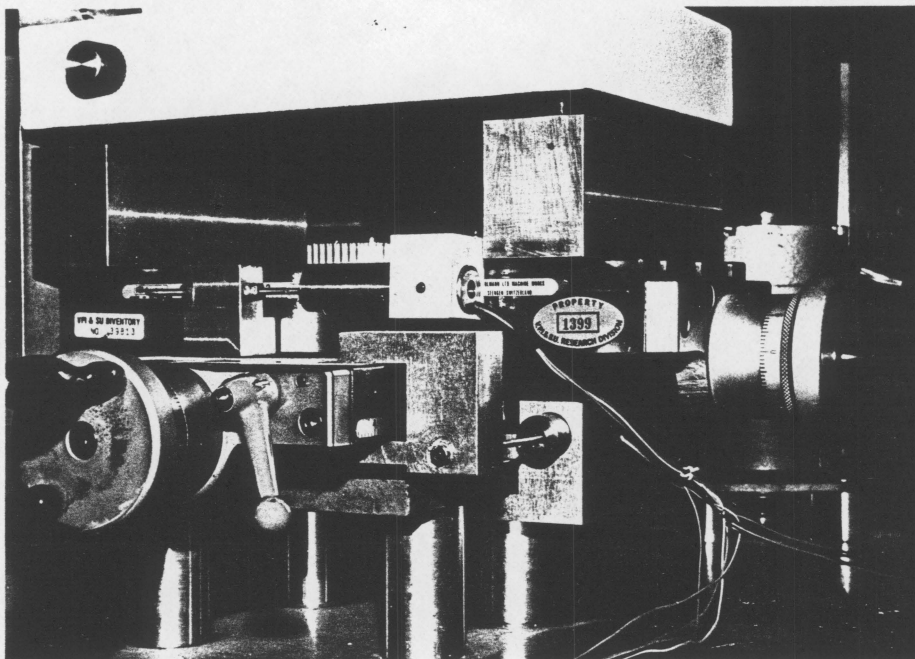
Figure 12. The LVDTs
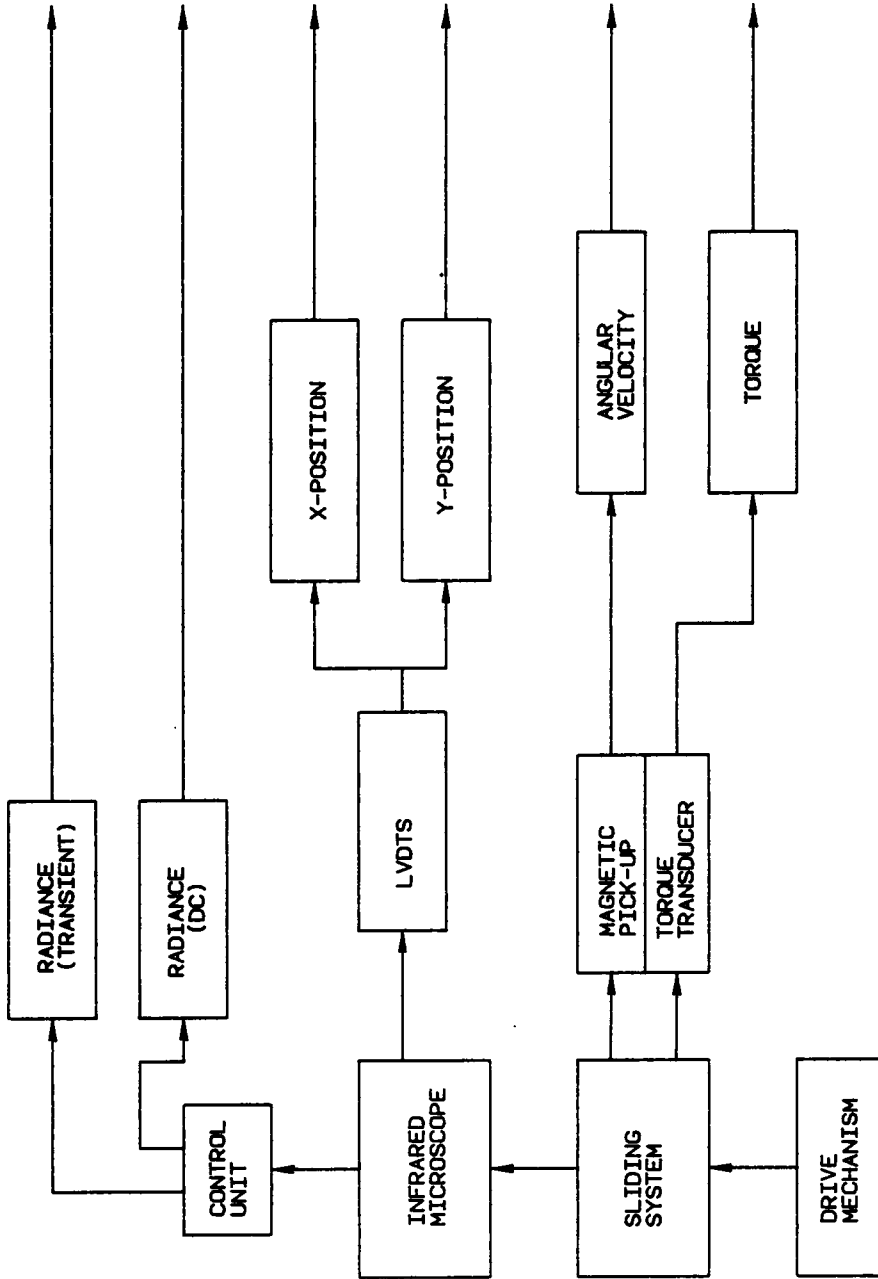
Figure 13. The Temperature Measurement System

4.3 The Data Acquisition and Processing System

A computerized data acquisition and processing system was developed and interfaced with the IR microscope and its accessories. The "brain" of the data acquisition system was an IBM personal computer. A Data Translation Analog and Digital Input/Output system was used as the digitizer and an IBM 4341 (host computer) was used as the data processor. Tektronix graphics terminals and various graphics and modeling software were used to display the data on cathode ray tube (CRT) monitors. Fig. 14 is a schematic diagram of the data acquisition system.

4.3.1 Data Translation Input Output (DT 2805 I/O) System

The DT 2805 [33] , manufactured by Data Translation Inc., USA, is a low cost, high performance analog to digital I/O system interface, compatible with the IBM PC. Full I/O functionality is provided on a single printed circuit board. Multiple boards can be plugged directly into any one of the IBM PC system expansion slots.

The DT 2805 includes a low level, wide range 12-bit analog/digital (A/D) converter system for 8 differential input channels (Fig. 15). A programmable gain amplifier provides selectable gains of 1, 10, 100 and 500, which allow the user to accomodate a 20 mV to 10 V full scale range of input signal levels. It also includes two 12-bit D/A converters and two 8 line digital I/O channels. An on-board programmable clock is included as a pacer clock for block mode A/D and D/A conversions.
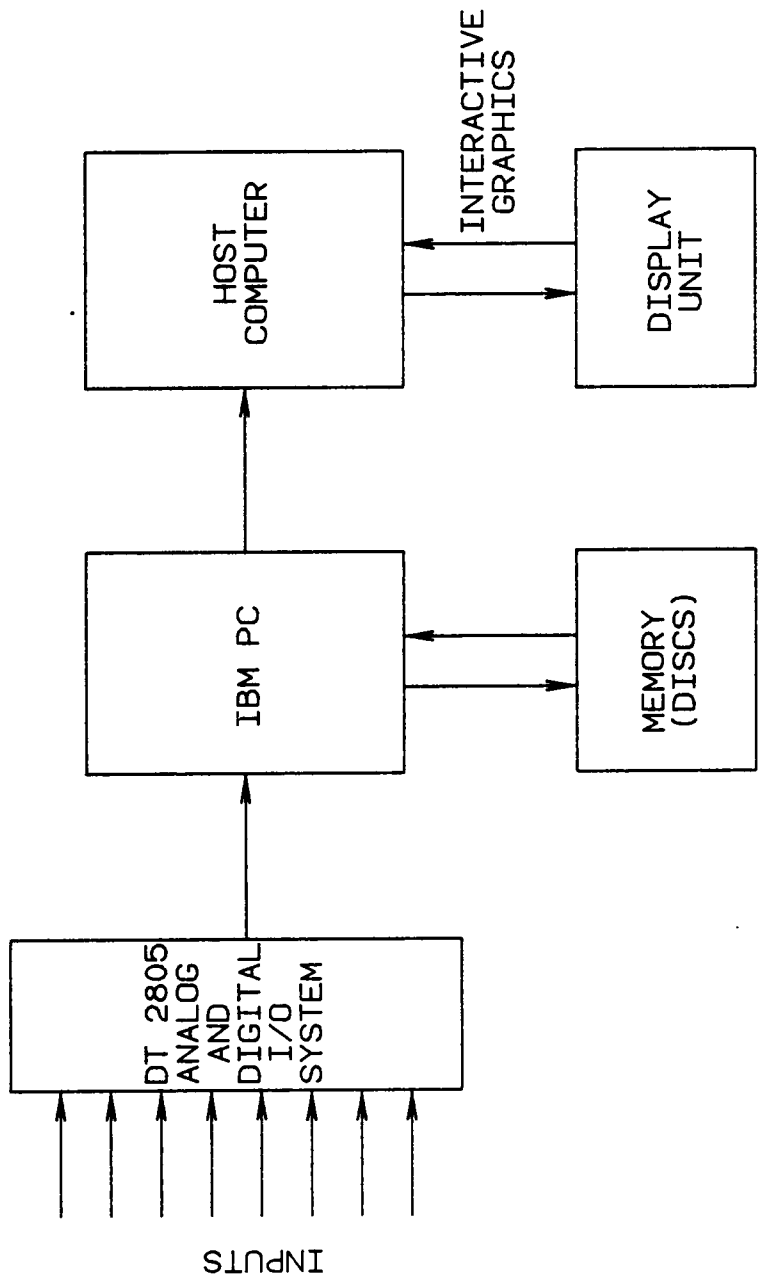
Figure 14. The Data Acquisition System (Schematic)
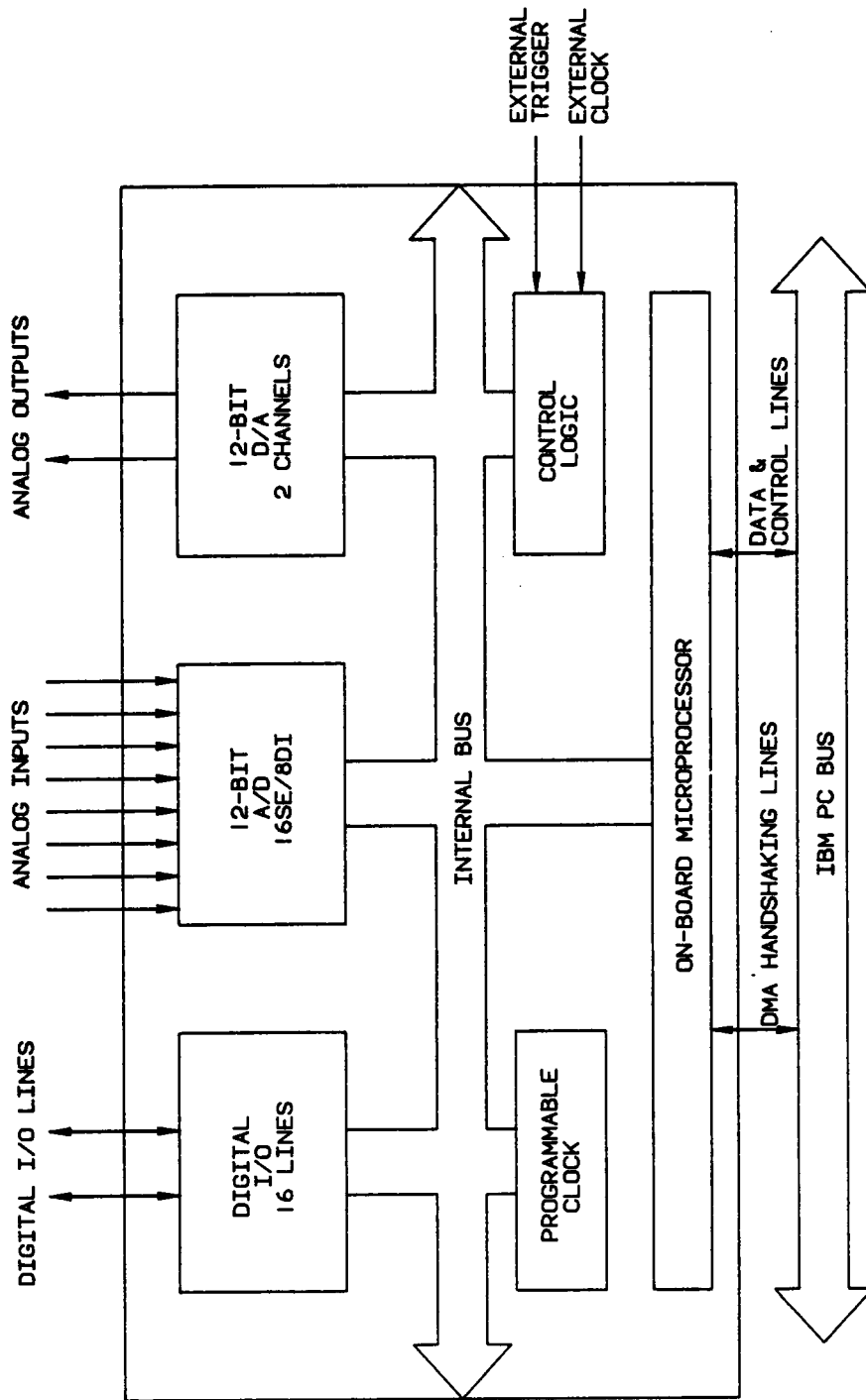
Figure 15. Block Diagram : DT 2805

This I/O card is designed around an on-board micro-processor which acts as the interface between the DT 2805 and the IBM PC. This microprocessor controls all on-board operations and simplifies program control by the IBM PC. Routine tasks, such as A/D converter sequencing and error checking, are carried out by this processor. The circuitry is also simplified to allow the board to fit within the chassis of the PC. The DT 2805 can be easily programmed in any language that accesses the IBM PC's I/O registers. Microcoding within the on-board controller greatly simplifies user access to the board's functions.

The on-board programmable clock is used to initiate repetitive data conversion events on the DT 2805. This internal clock is programmable for clock periods ranging from 5 microseconds to 0.1638 seconds in 2.5 microsecond increments, and can be used for internal clocking of A/D and D/A conversions. The board also provides for an external clock, which permits the synchronization of block mode A/D and D/A conversions with an external frequency source. An external trigger input allows the user to synchronize an I/O event with an external event by deferring command execution until an external trigger pulse is received. An on-board DC to DC power converter generates all needed analog supply voltages from the 5 V provided on the IBM PC back panel and provides high noise isolation from the computer system's power supplies.

A Data Translation 707 (DT 707) screw terminal panel (Fig. 16) provided ease of connection, via screw terminals, for all analog and digital signals, as well as trigger inputs, to the I/O board. It includes an integral one meter long flat ribbon cable for direct connection to the DT 2805.
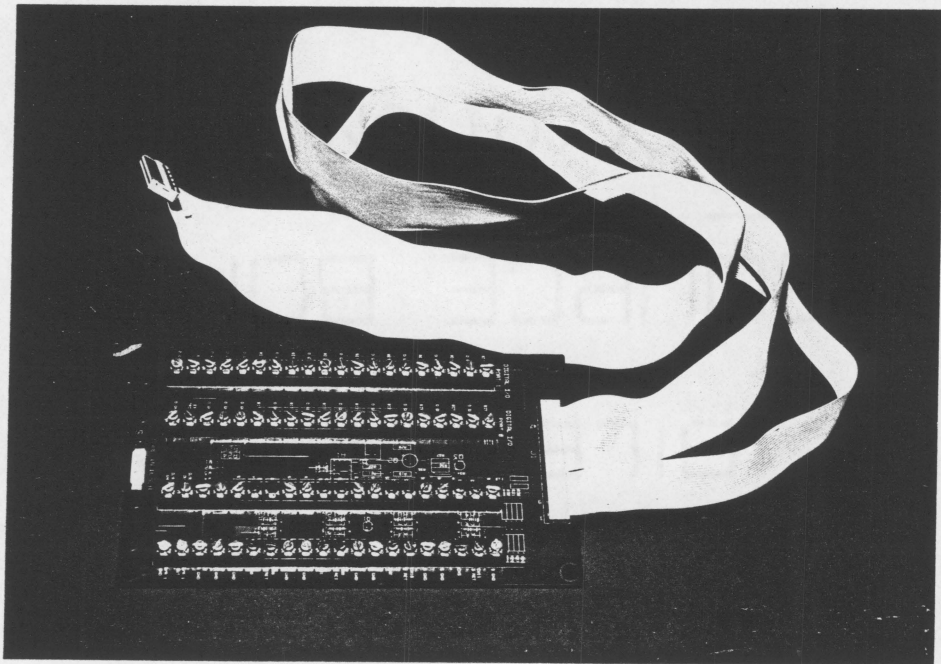
Figure 16. The Data Translation 707 Terminal Panel

4.3.2 The Data Acquisition Process

The outputs from the infrared microscope and its accessories were fed into the DT 2805 card through the DT 707 terminal panel. Since all these signals were analog in nature, the A/D converter channels of the I/O card were used. All the inputs were floating inputs and the digitizing sequence and other functions of the card were controlled locally by the IBM PC. Extensive interactive programs (in BASIC and FORTRAN 77) were developed to select the sampling rate, total number of samples, gain of the amplifier, the channels to be sampled and other such parameters. These programs were also used to set up a scanning region and generate the data required to make thermal "maps" of the region of interest.

The data thus generated was stored in 4 in. "floppy" discs for further processing before viewing. MOVIE.BYU was used for viewing the data on Tektronix terminals linked with the IBM 4341 computer. Interactive programs on the IBM 4341 VM/CMS system processed the data from the acquisition system and generated data files which could be directly read by the programs in MOVIE.BYU for graphics display.

5. Results and Discussion

Experiments were carried out with the two experimental set-ups discussed in the previous chapter. 3-D surface maps of some typical surfaces were generated from Talysurf data. Preliminary experiments were carried out with the temperature measuring system with the IR microscope focussed on target areas at known temperatures. Surface temperatures in sliding systems were also studied. All these experiments are discussed below with examples of results.

5.1 Surface Mapping

The surface mapping technique (discussed in the previous chapter) was used to generate 3-D maps of the surfaces of two different types of specimens. Both were steel specimens, 1 inch in diameter and 1/4 inch thick. One specimen was ground in one direction to produce an anisotropic surface. The CLA roughness of this specimen was found to be 0.50 micron (in a direction perpendicular to the direction of grinding). The other specimen surface was sandblasted to produce an isotropic surface. The CLA

roughness of this specimen was found to be 1.00 micron. An interactive computer program was used to manipulate the magnification of the profile heights, while the magnification in the X-Y plane was kept at a fixed value. This caused an exaggeration of the profile heights as compared with the other dimensions of the surface. A magnification factor of 1 was used to keep the magnification the same in all the three directions to get a true picture of the surface. The mapped area was a rectangle, 1.23 mm X 0.2 mm.

Some of the results of these tests are shown in Figs. 17 to 24. Figs. 17, 18, and 19 show a portion of the ground surface with different magnifications of the profile heights. Figs. 20, 21, and 22 show a portion of the sandblasted surface with different magnifications in the Z direction. Figs. 23 and 24 show contour maps of the two surfaces, with the contour lines representing places at the same elevation.

A sandblasted surface and a ground surface were chosen as the test surfaces because the topographies of the two can be easily distinguished from one another. A ground surface has a regular pattern of peaks and valleys whereas a sandblasted surface has a random distribution of peaks and valleys. The 3-D models of the ground surface (shown in Figs.17, 18 and 19) show a regular pattern of valleys and peaks. The valleys in the models represent grinding scratches. The random nature of the peaks in the model of the sandblasted surface can be seen in Figs 20, 21 and 22. These figures suggest that the mapping system was successful in generating true representations of the surfaces.

One of the most important advantages of this mapping system is that it gives the user the option to remove all the lines hidden from view and thus produce a more understandable view of the surface. Other important features, which make this system very versatile, are continuous tone image generation, global and local rotation, and zooming capabilities. These features not only help create realistic images of the surface, but also

44
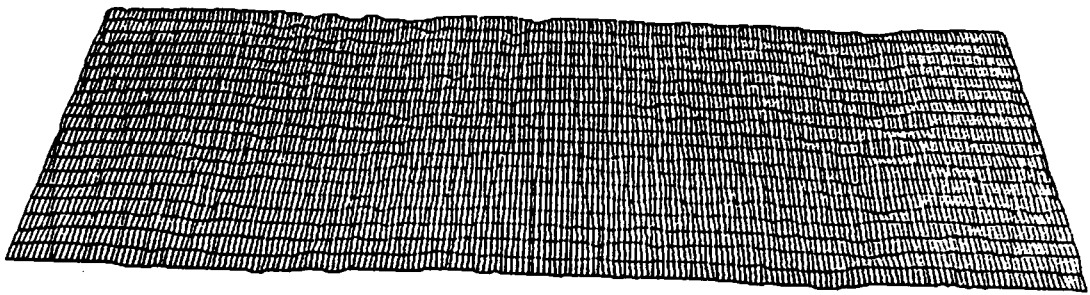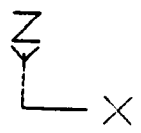
Figure 17. 3-D Map of Ground Surface (Ratio of Vertical to Horizontal Magnification = 1)

20 μ␈

Z
Y
X
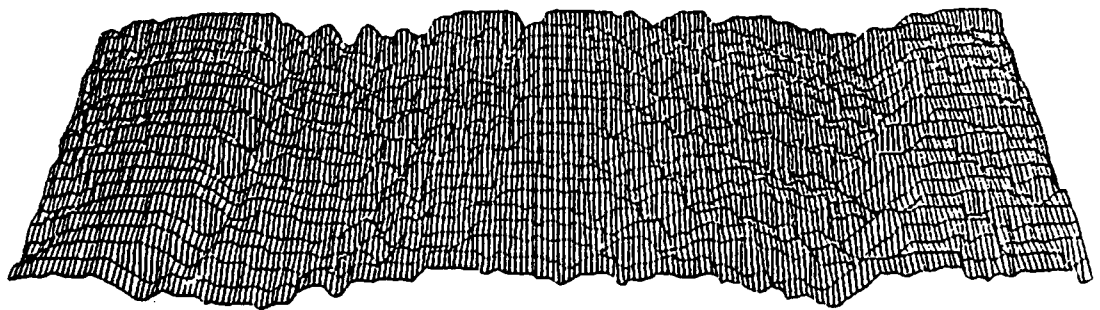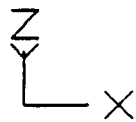
Figure 18. 3-D Map of Ground Surface (Ratio of Vertical to Horizontal Magnification = 5)
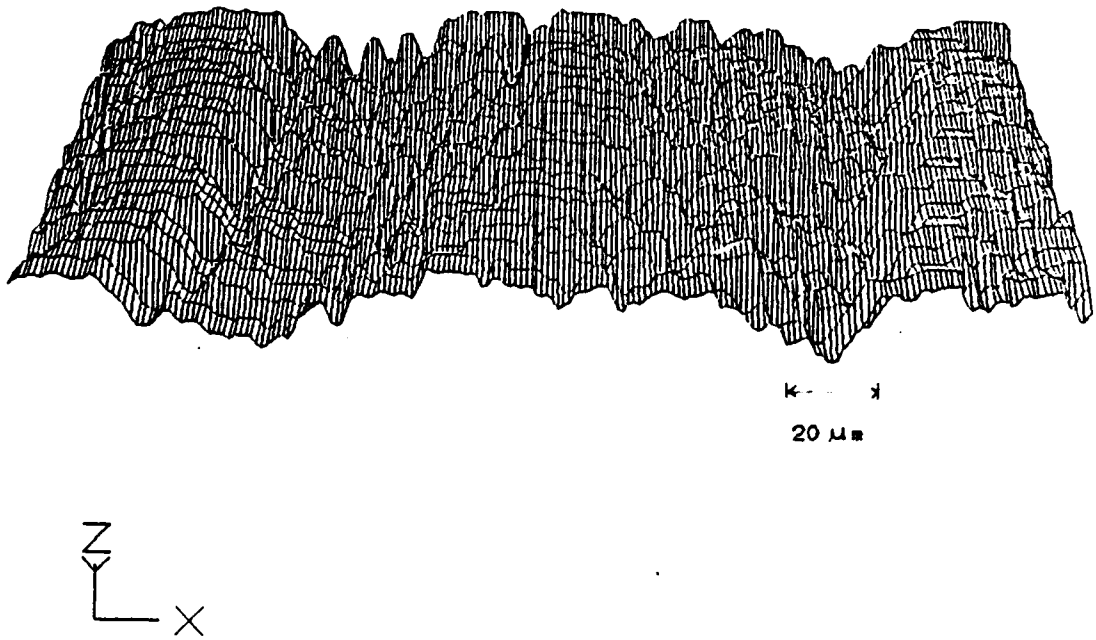
Figure 19. 3-D Map of Ground Surface (Ratio of Vertical to Horizontal Magnificaton = 10)
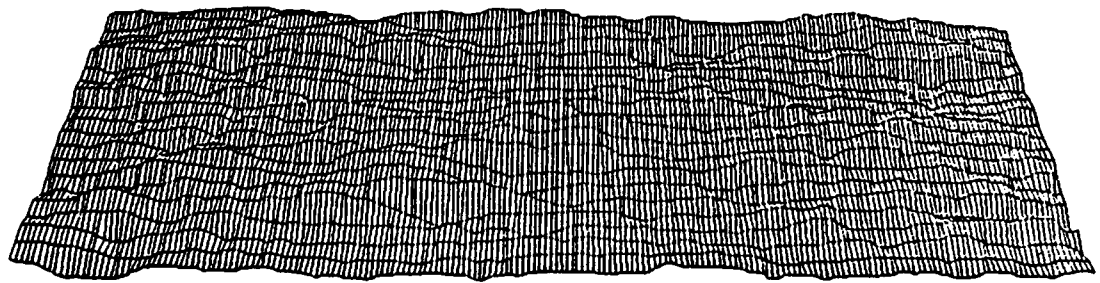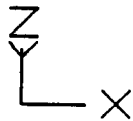
Figure 20. 3-D Map of San !blasted Surface (Ratio of Vertical to Horizontal Magni-
fication = 1)
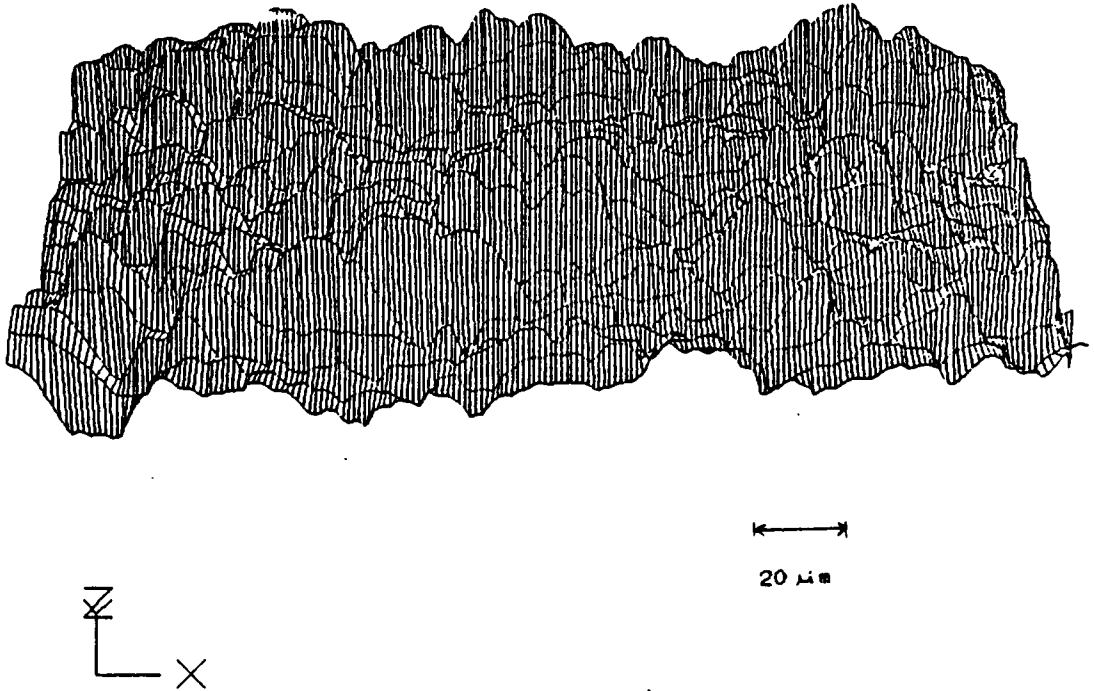
Figure 21. 3-D Map of Sandblasted Surface (Ratio of Vertical to Horizontal Magnification = 5)
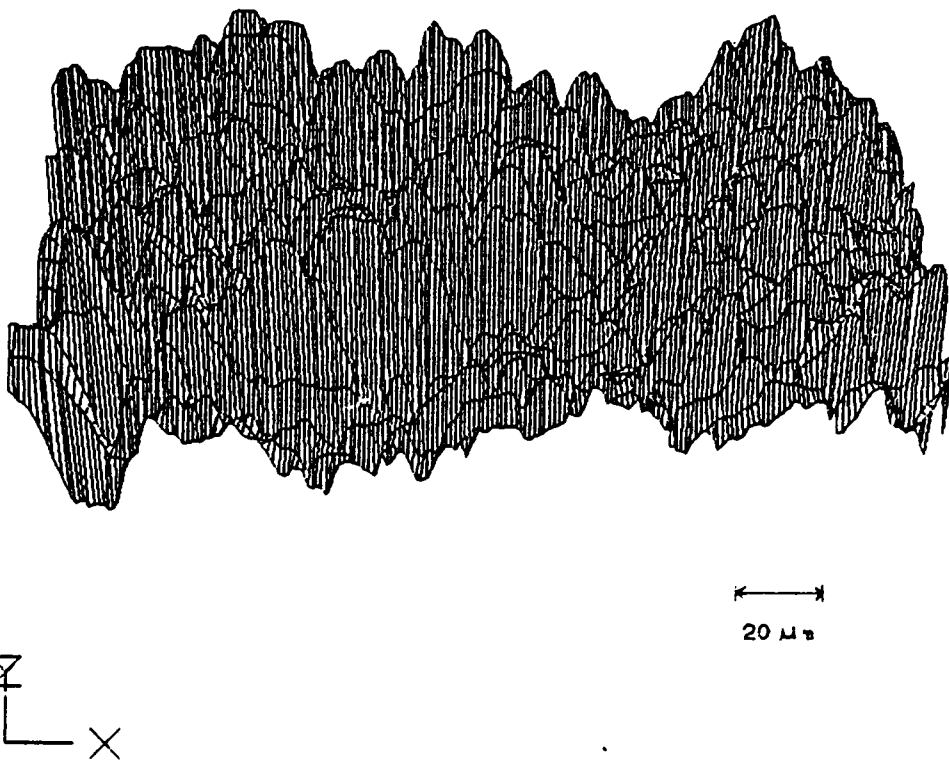
Figure 22. 3-D Map of Sandblasted Surface (Ratio of Vertical to Horizontal Magnification = 10)
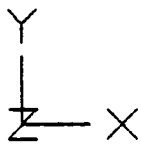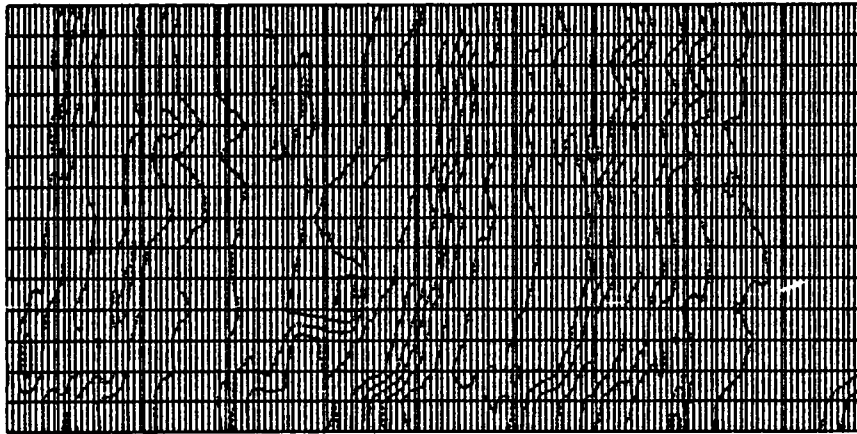
Figure 23. Contour Map of Ground Surface
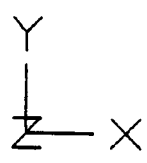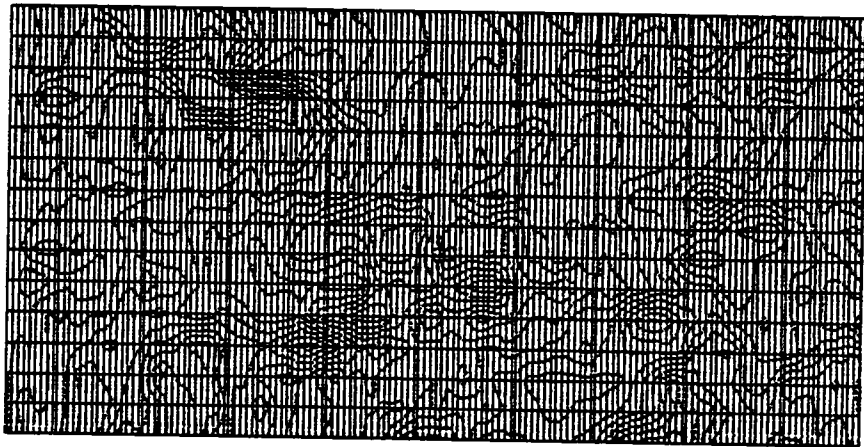
Figure 24. Contour Map of Sandblasted Surface

allow the user to rotate the model and zoom in or zoom out to a suitable viewing position.

If two solids are placed in contact, the asperities of the surfaces come in contact first. Then they deform as the load increases and the true area of contact changes. This true area of contact is different from the nominal area of contact except when the surfaces are perfectly smooth. Most of the surfaces used in engineering applications have surface irregularities greater than 1000 A [34]. Thus it is very difficult to determine the true area of contact and the number of contact points. The models generated by the mapping system developed in this study can help solve this problem. Figs. 25 to 28 show examples of how this system can be used to simulate two surfaces coming in contact with each other. The top views (Figs. 26 and 28) show the initial areas of contact when the surfaces come in contact with a flat surface. These "areas of contact" have been determined by slicing off the tops of the peaks in contact with the flat. This is not necessarily true. Usually, the initial area of contact is determined by the plastic and/or elastic deformation of the two members coming in contact. This modeling technique, combined with analysis packages (e.g., finite element analysis) may help predict the true area of contact, location of areas of high stress, etc., and may become an invaluable tool which will assist the tribologist in research, teaching, and simulation of tribological systems.

10 μm
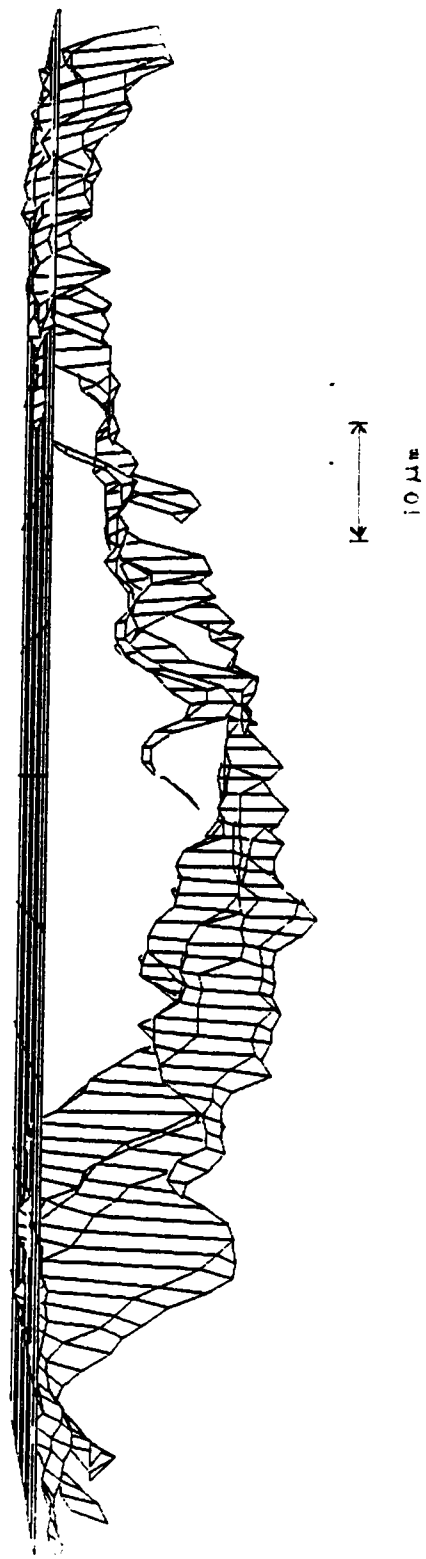
Figure 25. Contacting Surfaces--Ground Surface and Flat (Side View)
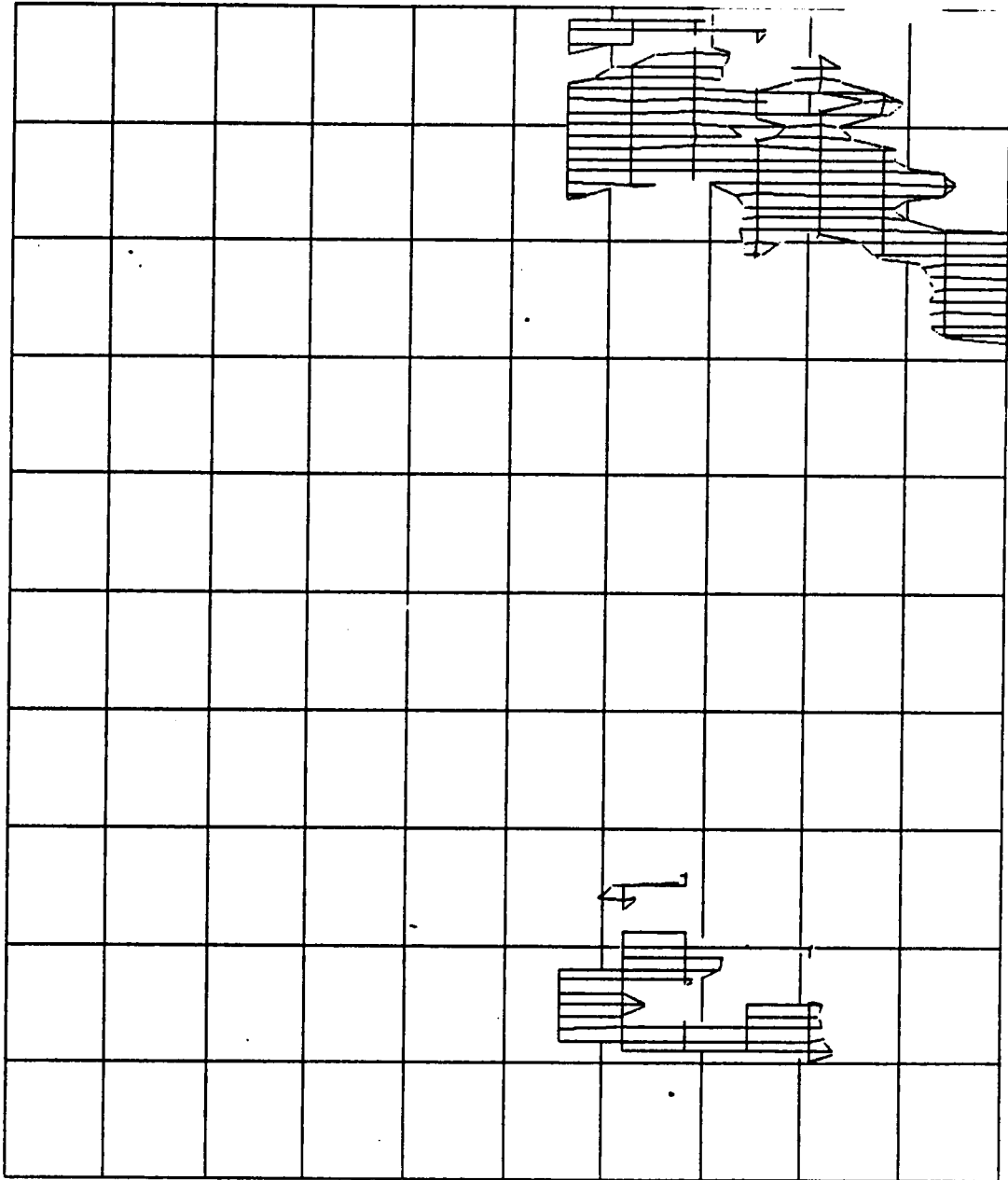
Figure 26. Contacting Surfaces--Ground Surface and Flat (Top View)

10 μm
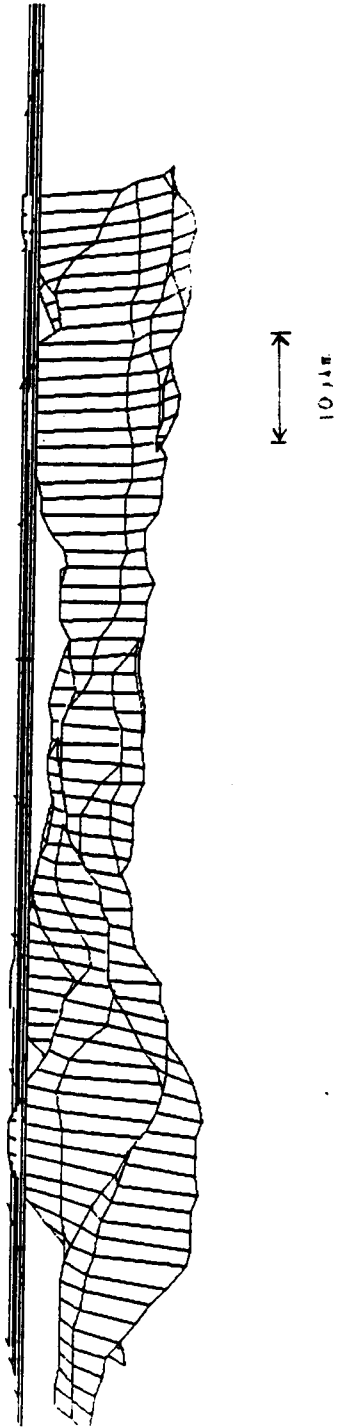
Figure 27. Contacting Surfaces--Sandblasted Surface and Flat (Side View)
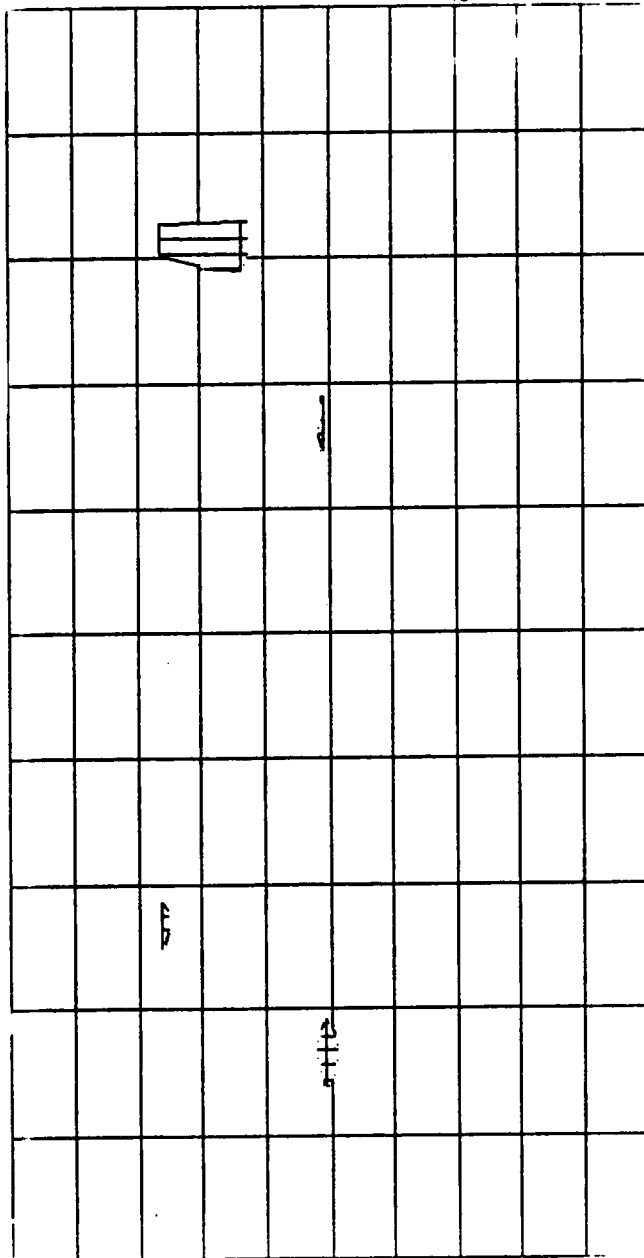
Figure 28. Contacting Surfaces--Sandblasted Surface and Flat (Top View)

5.2 Surface Temperature Measurements

5.2.1 Radiance Mapping

5.2.1.1 Preliminary Experiment

As mentioned before, a preliminary experiment was carried out with the IR micro-scope focussed on a target area at a known temperature. A Barnes Model RM 121-1 Radiometric Calibration Source (Fig. 29) was used as the source of IR radiation for this experiment. The Calibration Source consists of an IR radiation source cavity and a wide range temperature controller. The cavity temperature can be regulated over the range of $60^{\circ}C$ to $230^{\circ}C$. A thermocouple inserted in the cavity was an independent means of checking the temperature.

The microscope was focussed on the center of the cavity (at room temperature), and the output (DC) was zeroed using the Ambient Control dial on the control unit. The scanning region was then set up (as shown in Fig. 30) using the computerized system. The total scanning area was 0.45 in. x 0.45 in. with adjacent sampling points spaced 0.05 in. apart in both the X and Y directions, generating a 9 x 9 grid. The microscope was then moved away and the Calibration Source heater was turned on with the temperature controller set at $100^{\circ}C$. After 20 minutes, the temperature of the cavity stabilized (as noted by the output from the thermocouple). The microscope was then brought back to position and moved back and forth over the scanning region in a zig-zag manner (as shown in Fig. 31). The signal from the DC output was averaged over 20 samples, for
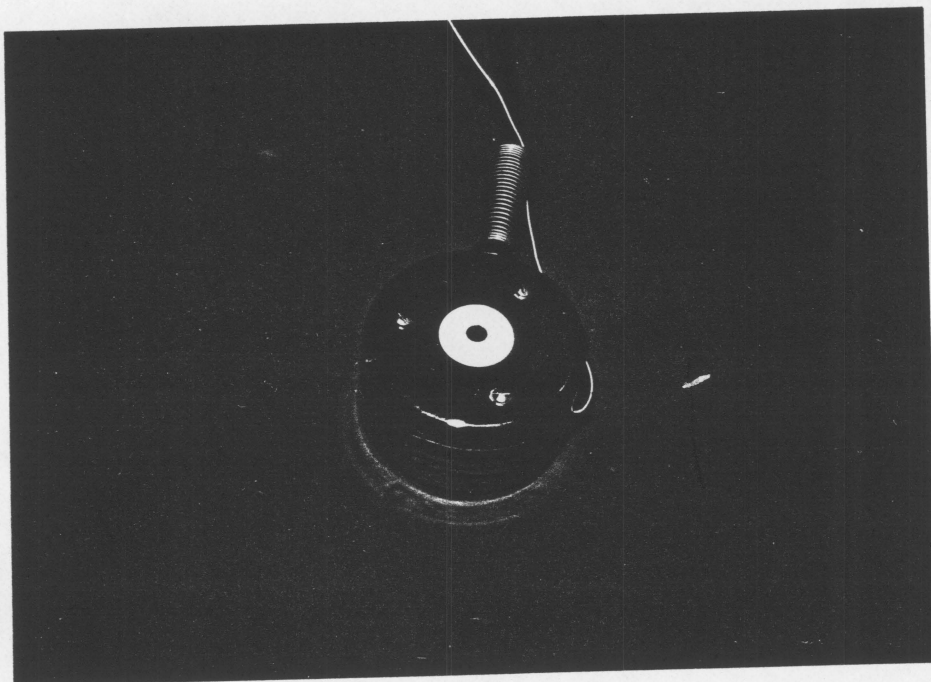
Figure 29. The Barnes Radiometric Calibration Source

MAPPING
REGION

CAVITY
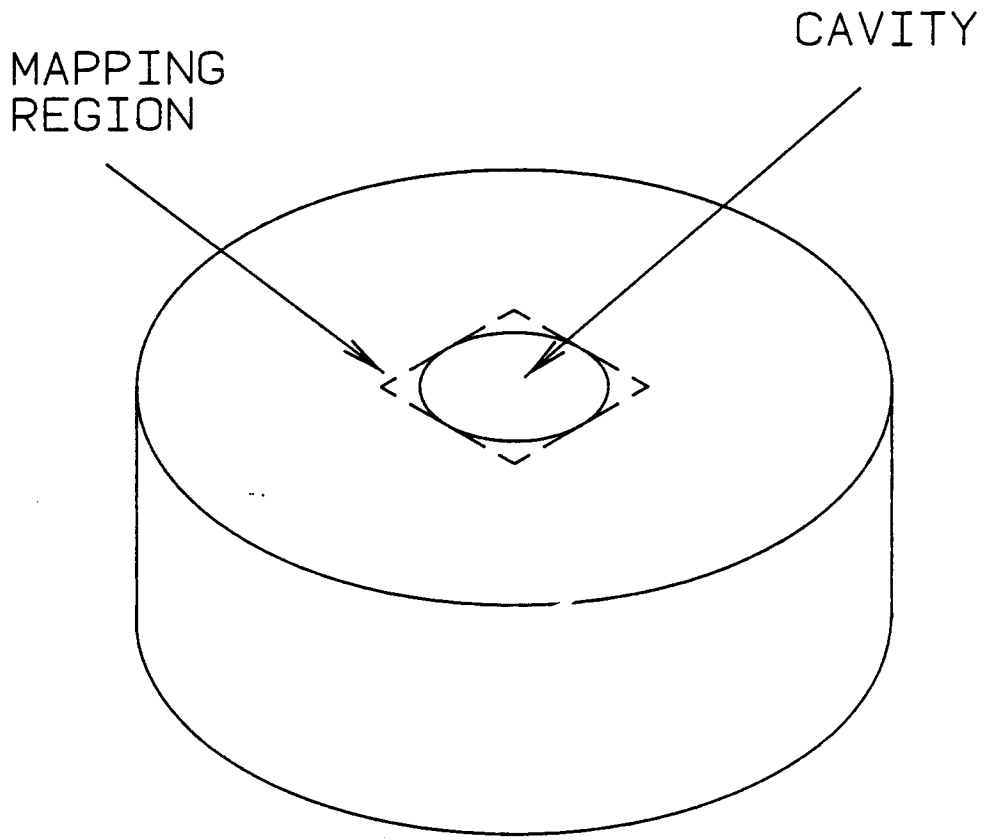
Figure 30. The Scanning Region
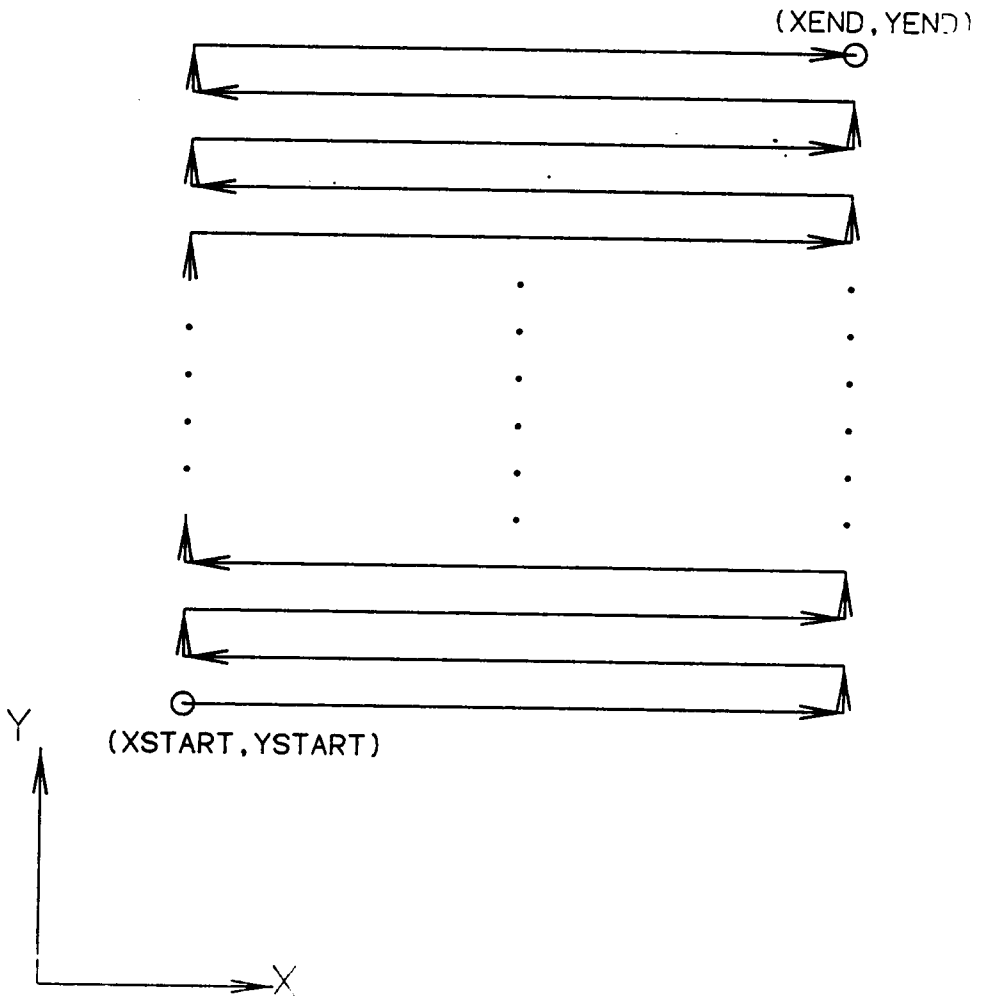
Figure 31. The Scanning Method

each node, and the final array of the radiance values (in Volts) was stored on a floppy disc.

The data from the above experiment was transferred to the IBM 4341 computer and processed by FORTRAN programs to generate files containing the information necessary for viewing the data using MOVIE.BYU. Different methods of representing the data were tried. Figs. 32 and 33 show three-dimensional representations of the radiance map. In this method, the X-Y plane represents the target area over which the radiance was measured. The Z axis represents the the radiance output from the DC channel of the control unit. Fig. 32 shows the radiance map over the entire region whereas, in Fig. 33, the 3-D geometry has been treated as shell elements with removal of hidden lines. This facilitates viewing the 3-D map without much confusion being created by the polygon boundaries. Fig. 34 and Fig. 35 show the same geometry from a different viewing angle and with different scales for the radiance values.

Fig. 36 shows a contour map of the radiance over the mapping region. In this viewing method, the values of the radiance at the nodes of the grid were stored in a scalar "Function File", which was read by MOVIE.BYU to generate contours showing places having the same scalar value. The geometry shown in this figure is a flat planar shell representing the region of interest. Since the radiance values were known only at the nodes, MOVIE.BYU used a linear interpolation technique to determine the values at all points between the nodes, before generating the contours. Fig 37 shows a combination of both the viewing methods discussed above--3-D representation and contour mapping. In this figure, the contour lines represent points at the same elevation (i.e., same value of the Z coordinate).
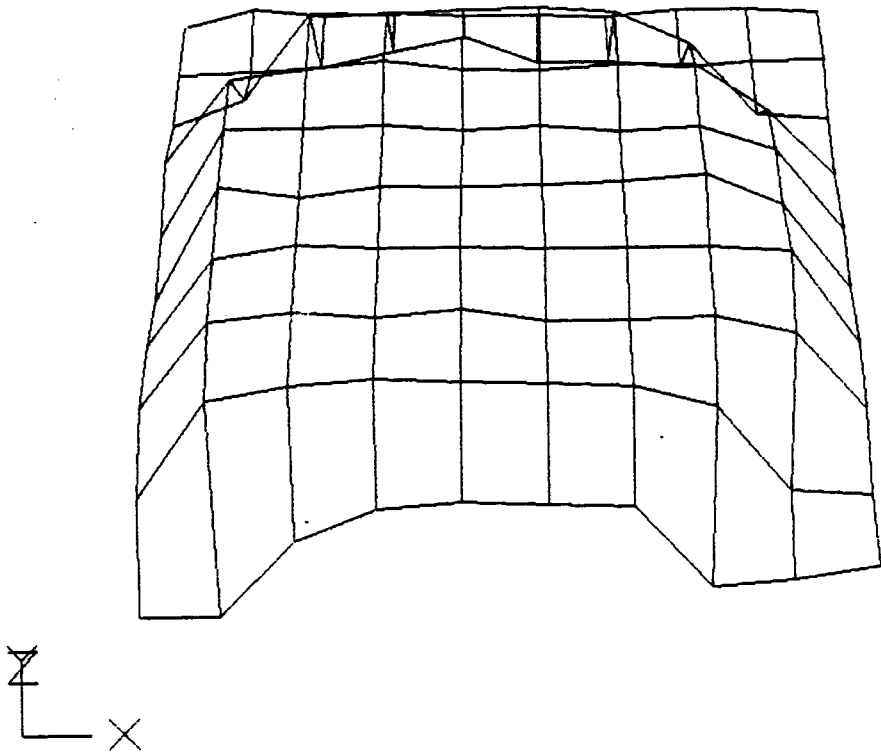
Figure 32. 3-D Representation of Radiance (Without Hidden Line Elimination)
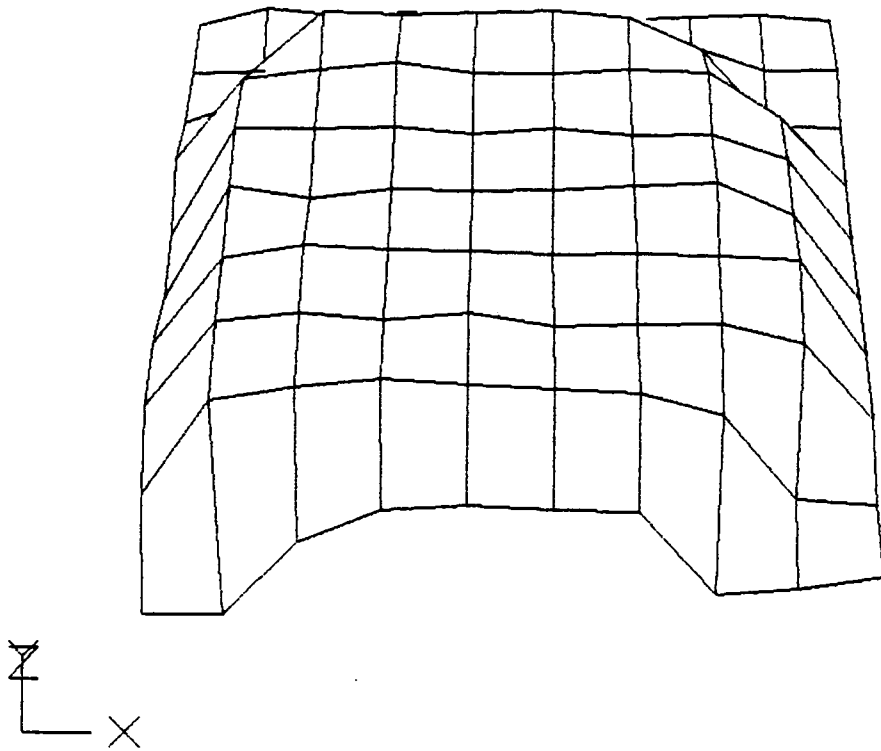
Figure 33. 3-D Representation of Radiance (With Hidden Line Elimination)
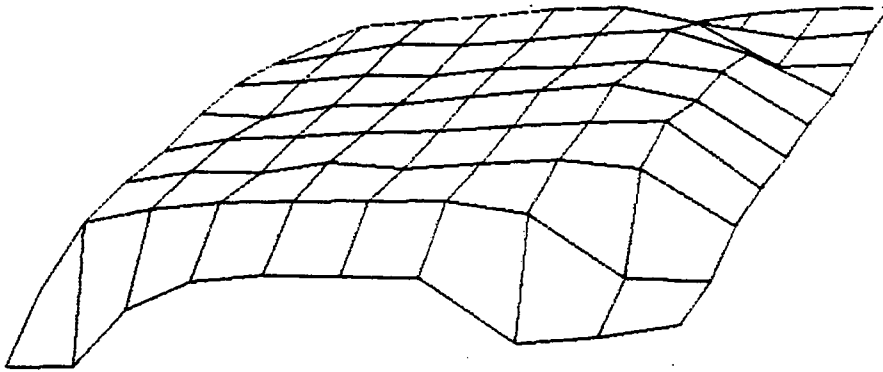
Figure 34. 3-D Representation of Radiance (0.5 X magnification in Z direction)
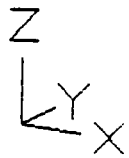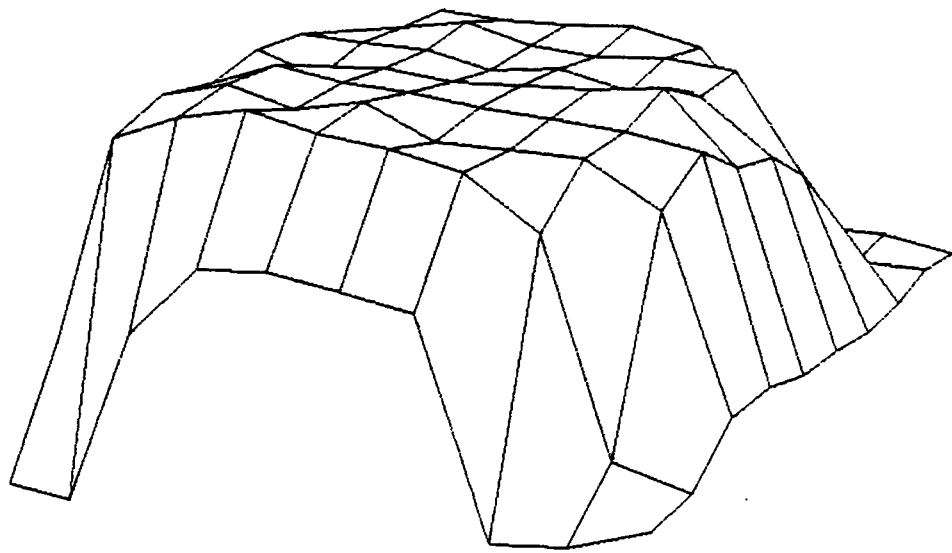
Figure 35. 3-D Representation of Radiance (1.5 X magnification in Z directions
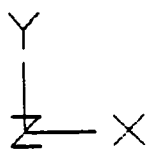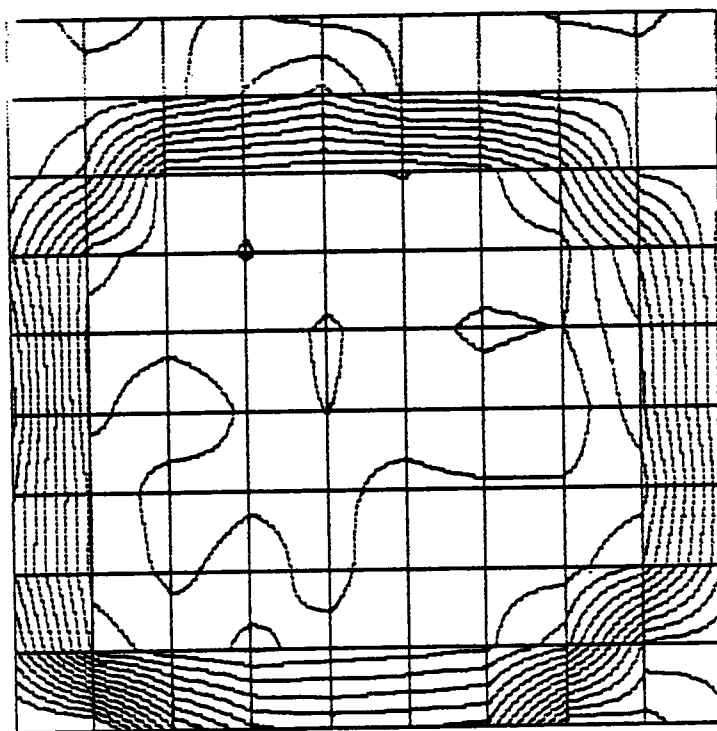
Figure 36. Contour Map of the Scanned Region
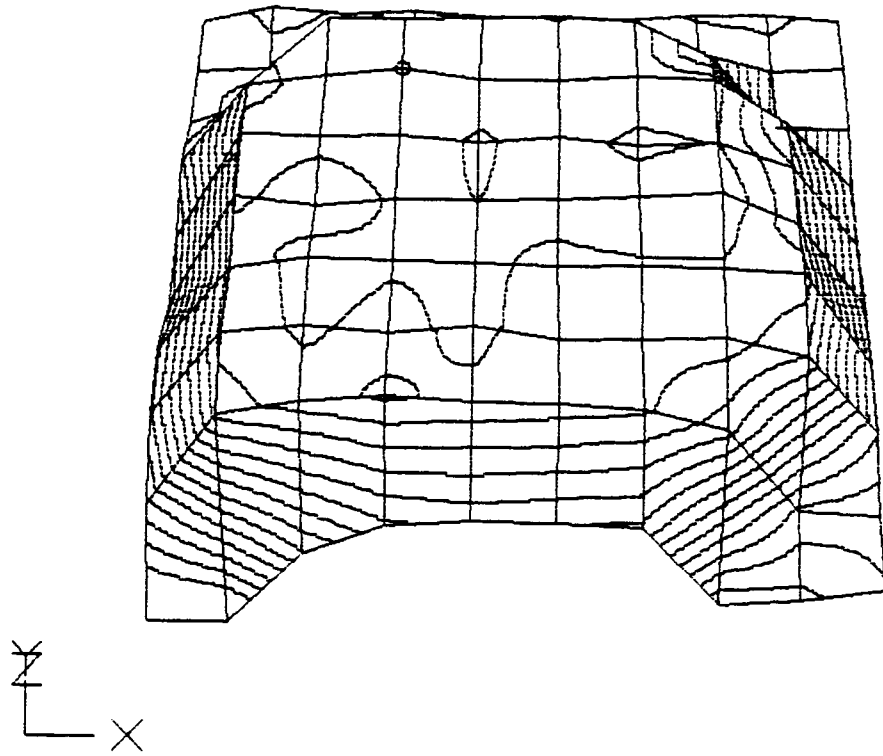
Figure 37. 3-D Representation of Radiance and Contour Mapping

In Fig. 38, "color fringing" has been used to represent the radiance values over the mapping region. In this technique, different colors have been used to represent different IR radiation levels. The colors used were blue, cyan green, yellow, and red, with blue representing the lowest radiation level and red representing the highest. Fig. 39 shows a combination of the 3-D representation and the color fringing techniques.

From the results of these experiments it can be concluded that the temperature mapping system was functioning properly. The radiance was higher in a circular region inside the square mapping area. This was as expected because, in the experiment, the mapping region enclosed the circular cavity of the Calibration Source. In Fig. 38 the circular hole seems to be represented by a rectangular area. This was because of the large size of the finite element grid chosen. This drawback could have been avoided by using more nodes within the same area. All the viewing techniques used gave a very good representation of the radiance distribution over the area of interest.

5.2.1.2 Sliding Systems

The radiance mapping system was tested with various different specimens, i.e., iron, copper, silver, and polyethylene sliding against sapphire. The test conditions are given in Table 1. Prior to a test, the sapphire disc was cleaned with hydrochloric acid, distilled water, acetone, and distilled water, in that order. The instrumentation was then turned on, allowed to stabilize, and then zeroed. The specimen was mounted on its holder and loaded against the disc. The microscope objective was focussed on the interface and the scanning region set up (as explained in the previous section). The motor was then turned on and scanning was started one minute later.
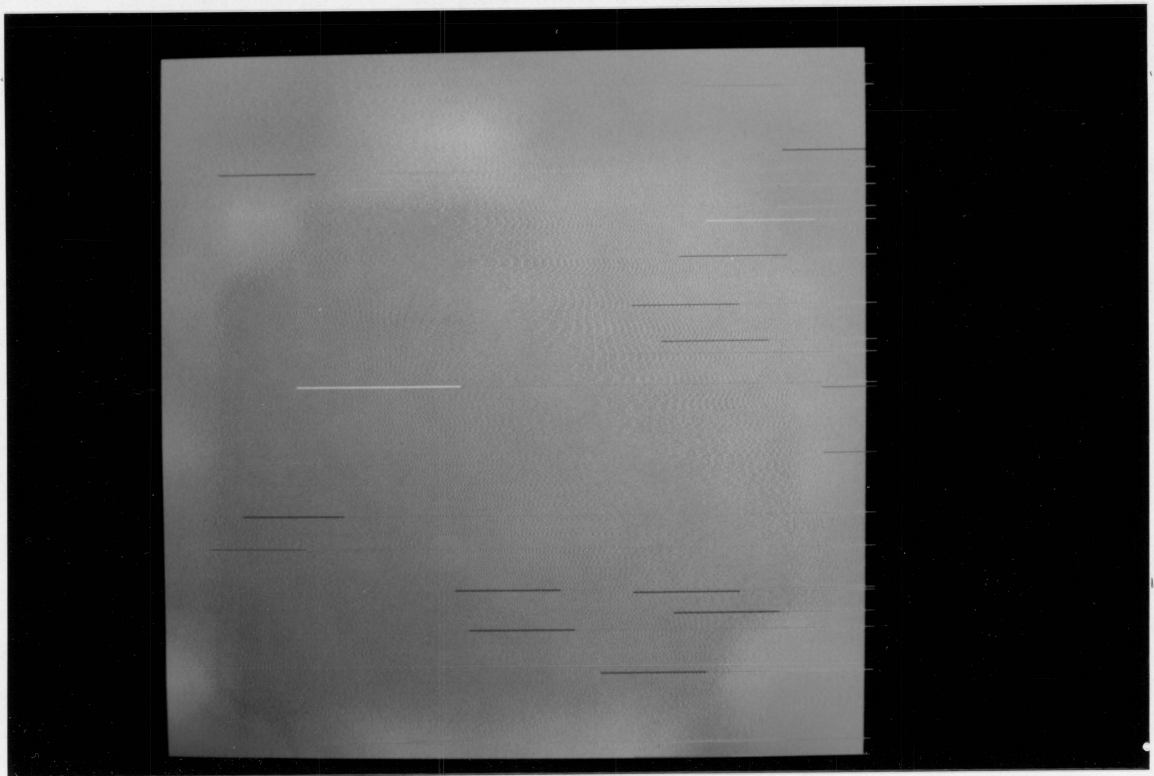
Figure 38. Color Fringing Technique
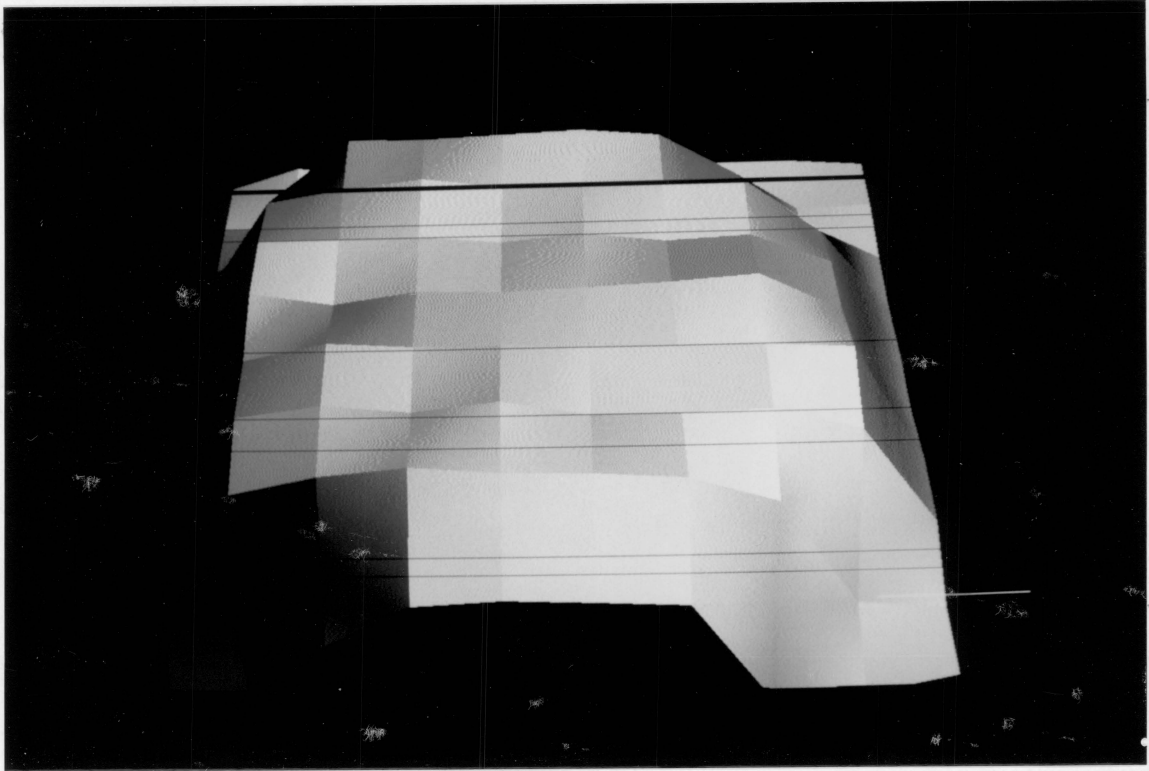
Figure 39. 3-D Representation of Radiance and Color Fringing

TABLE 1 - Test Conditions (Radiance Mapping)

TEST NO.	SPECIMEN	GEOMETRY	SLIDING VELOCITY (m/s)	SCANNING AREA	LOAD (N)
1	IRON	PIN (3.5 mm DIA HEMISPHERICAL HEAD)	2.394	3.81 X 3.81 mm	2.45
2	SILVER	PIN (3 mm DIA CONICAL HEAD)	2.394	6.35 X 6.35 mm	2.45
3	COPPER	PIN (5 mm DIA CONICAL HEAD)	2.394	5.08 X 5.08 mm	2.45
4	POLYETHYLENE	SPHERE (6.35 mm DIA)	2.394	5.08 X 5.08 mm	2.94
5	COPPER	PIN WITH SLIT	2.394	2.54 X 2.54 mm	2.45

The tests were carried out on Fe, Ag, polyethylene, and two different types of Cu specimens. Both the Cu specimens were in the form of pins, but one of them had a slit in the middle (as shown in Fig. 40). Before scanning the region of contact for the Cu specimen with the slit, the slit was aligned with one of the axes of the scanning plane with the help of the crosshair in the microscope eyepiece. In all the tests, the sliding direction was along the X-axis of the scanning plane.

Results of these experiments are shown in Figs. 41 to 55. For each test, two different views of the 3-D representation of the radiance map and one view of the contour map are shown. The Fe specimen was mapped first, with the scanning region divided into a 10 X 10 grid.

It can be seen from Figs. 41 to 43 (radiance maps for the Fe-on-sapphire system) that, as expected, the radiation increased towards the center of the scanning region (since the scanning region was larger than the macroscopic area of contact). However, the grid size was too large to give a proper representation of the radiance distribution over the area of contact. Hence, for the other tests, a 20 X 20 grid was used for scanning the area.

Figs. 44, 45 and 46 represent the results of radiance mapping for the Ag specimen. For this system, it is quite difficult to distinguish the region of contact from the region which is not in contact, from the radiance map. This could be due to transfer of material to the disc. On completion of this experiment, there was evidence of some oxide transfer to the disc; this could have blocked out some of the radiation coming from the region of contact.

.32 MM

2 MM
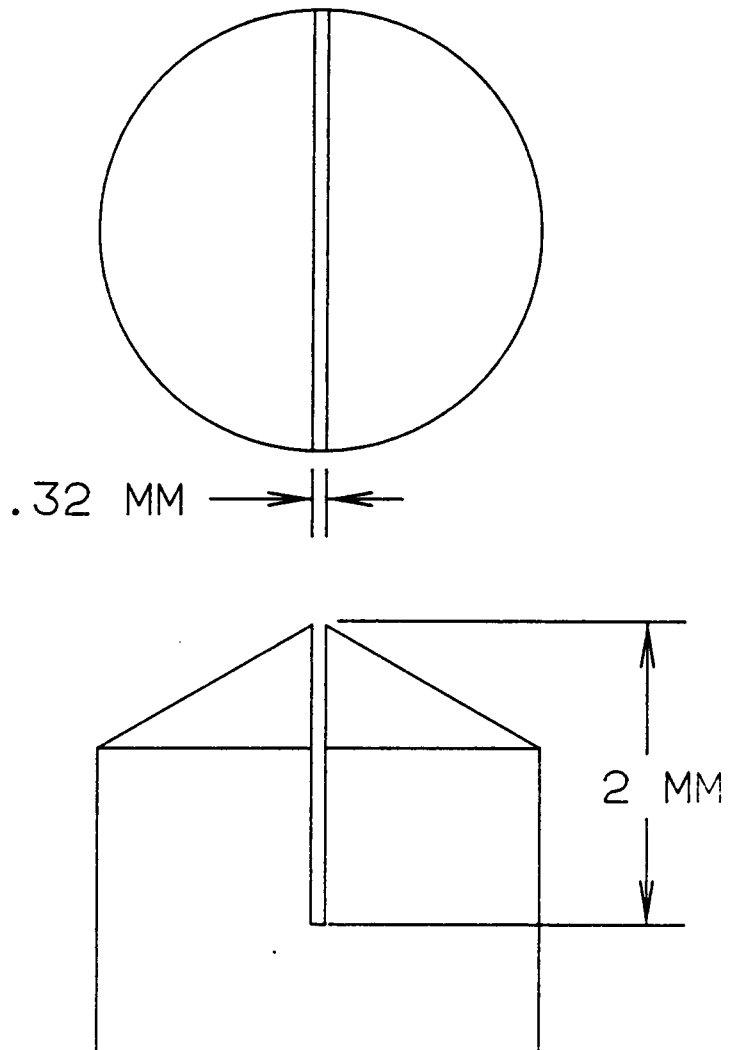
Figure 40. Copper Specimen with a Slit
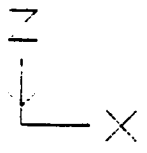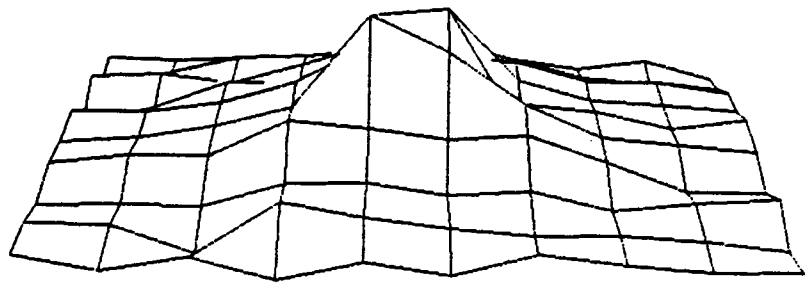
Figure 41. 3-D Representation of Radiance using Iron Specimen (view 1)
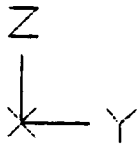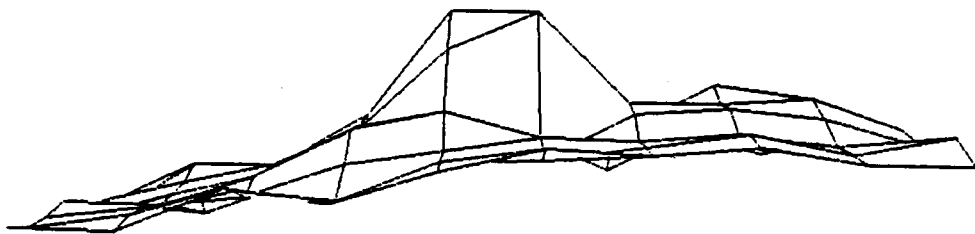
Figure 42. 3-D Representation of Radiance using Iron Specimen (view 2)
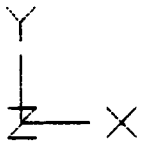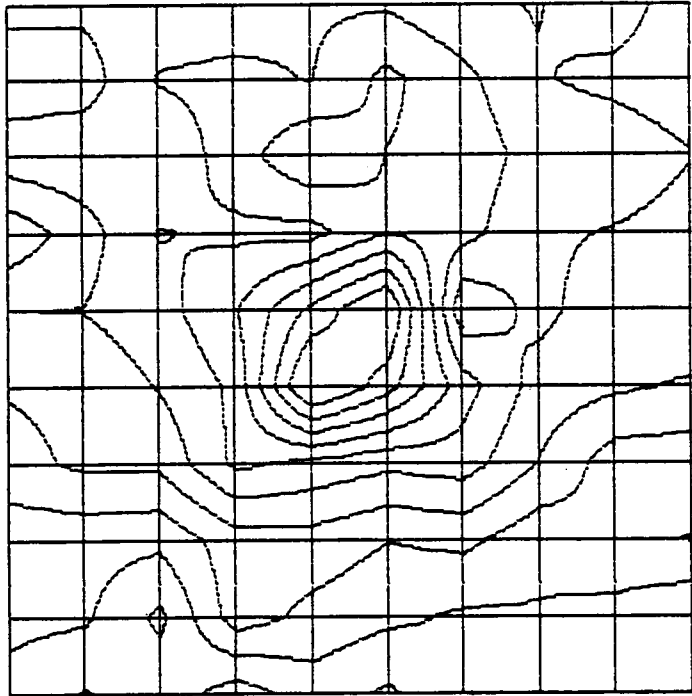
Figure 43. Contour Map of Radiance using Iron Specimen
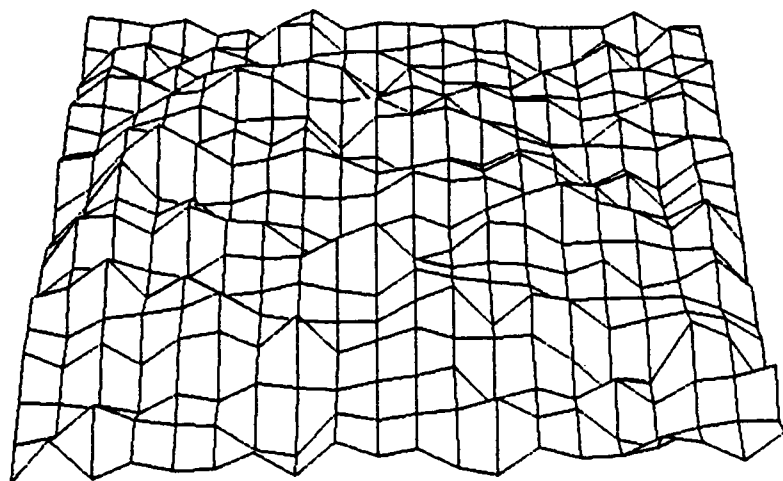
Z
X

Figure 44. 3-D Representation of Radiance using Silver Specimen (view 1)
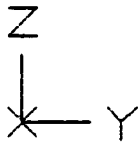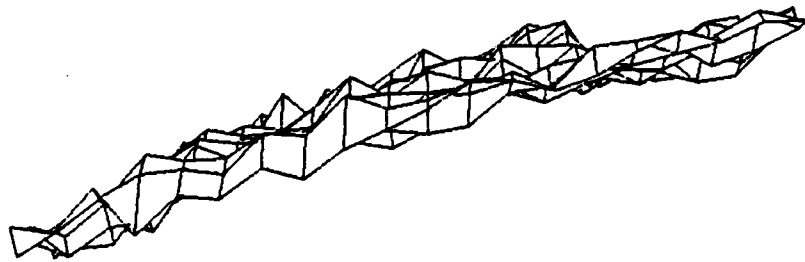
Figure 45. 3-D Representation of Radiance using Silver Specimen (view 2)
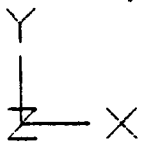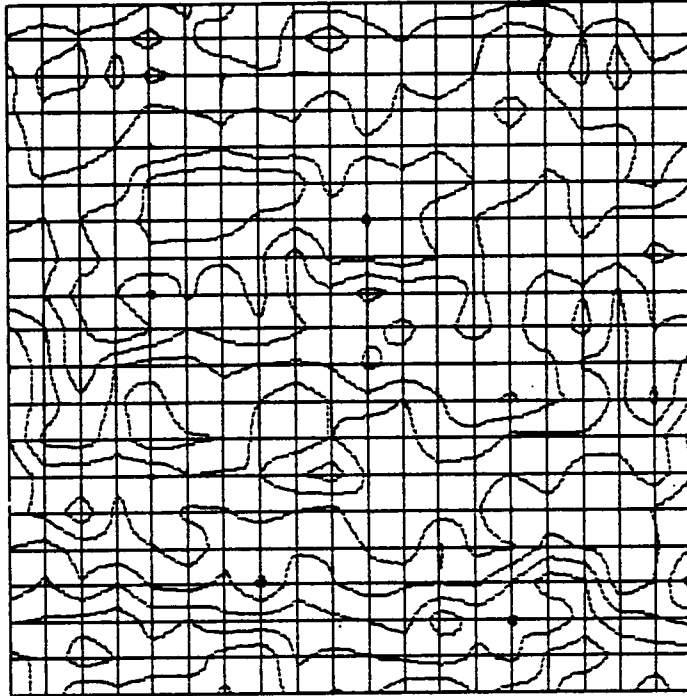
Figure 46. Contour Map of Radiance using Silver Specimen

Figs. 47, 48 and 49 show the radiance map for the Cu-Sapphire system. In the radiance maps for this system, the region of contact can be easily seen as the region showing a higher radiance level.

Figs. 50, 51 and 52 show the radiance maps for the Polyethylene-Sapphire system. In this case too (as observed with Ag) the region of contact can not be determined from the radiance maps. It is important to note that for each system, scanning the region of interest took 10 to 15 minutes and hence the radiance map is a function of both time and position. It is possible that the area of contact for the polyethylene-sapphire system increased during the scanning, which would account for the continuous increase in radiance along the Y-axis as shown by Fig. 51. Another possible reason for this character of the map is that material transfer from the specimen to the disc could have blocked out some of the radiation from the area of contact. Thus, moving the microscope out of the region of contact would increase the radiation to the microscope due to the absence of transferred material, and the map can be expected to show high radiance values outside the region of contact.

The radiance maps for the second Cu specimen (with the slit in the middle) are shown in Fig. 53, 54 and 55. The radiance level in this system is lower along the centerline of the scanning region, indicating either a region at a lower temperature or a region with a lower surface emissivity. In this particular system, it is known that this depression in the map is due to the slit in the specimen.

An important fact to be noted from all these results is that, for every system, the radiance level seems to increase along the Y-axis. This can be explained by the fact that it took about 10 to 15 minutes to scan the mapping region and obtain the data necessary for the map. Since the scanning was started within a minute of the commencement of sliding, the system was not given enough time to reach steady state. Hence, as the scanning progressed, the temperature at the interface also increased. Since the microscope was shifted along the Y-axis after every scan line, the radiance seems to increase along this axis, although this increase actually represents an increase in radiance with time.

It is also important to realize that all these radiance maps discussed above are essentially maps of the voltage levels from the DC channel of the IR microscope. If the radiance - voltage relationship is linear in nature, these maps also represent the true nature of the radiance maps. However, the true nature of the temperature maps cannot be inferred from these radiance maps. The conversion from radiance to temperature involves the surface emissivity of the specimen. This emissivity is not always constant over the entire region of contact, nor is it constant with time (since the surface is changing constantly). Emissivity also depends on the temperature at the surface. Thus, in order to get accurate temperature maps, the emissivity of the surface has to be deter-
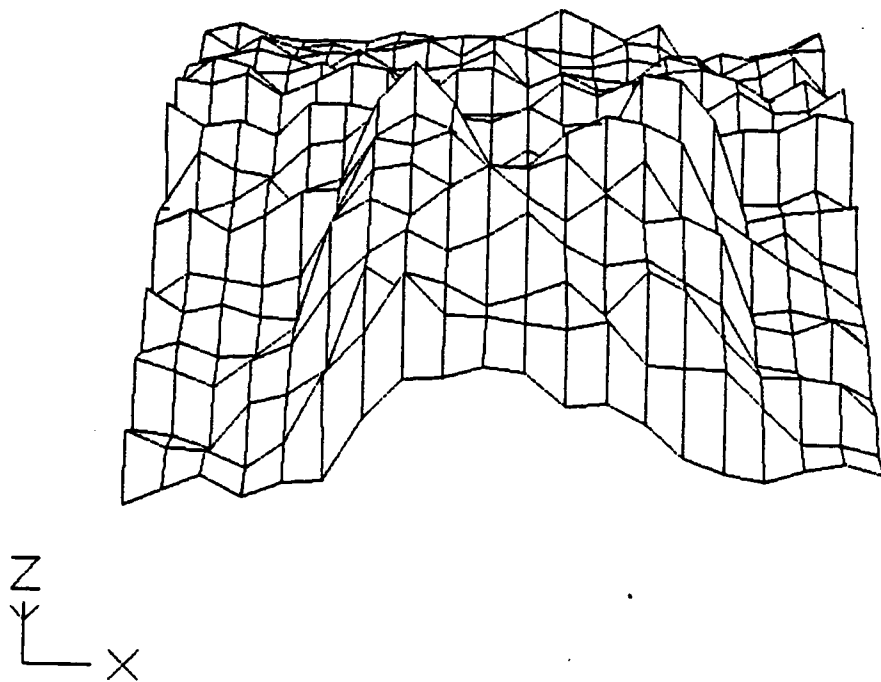
Figure 47. 3-D Representation of Radiance using Copper Specimen (view 1)

Z
Y
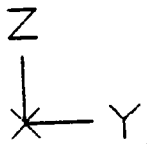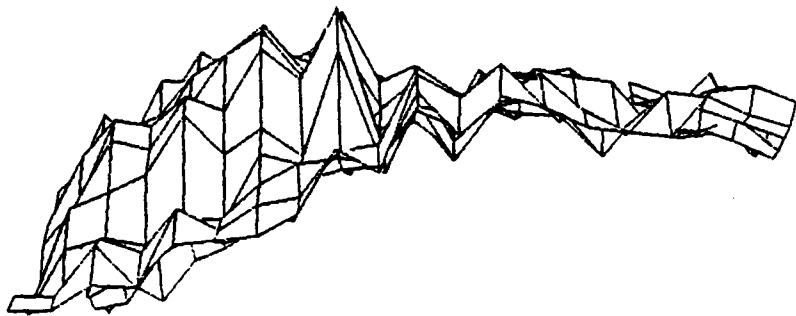
Figure 48. 3-D Representation of Radiance using Copper Specimen (view 2)
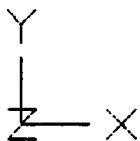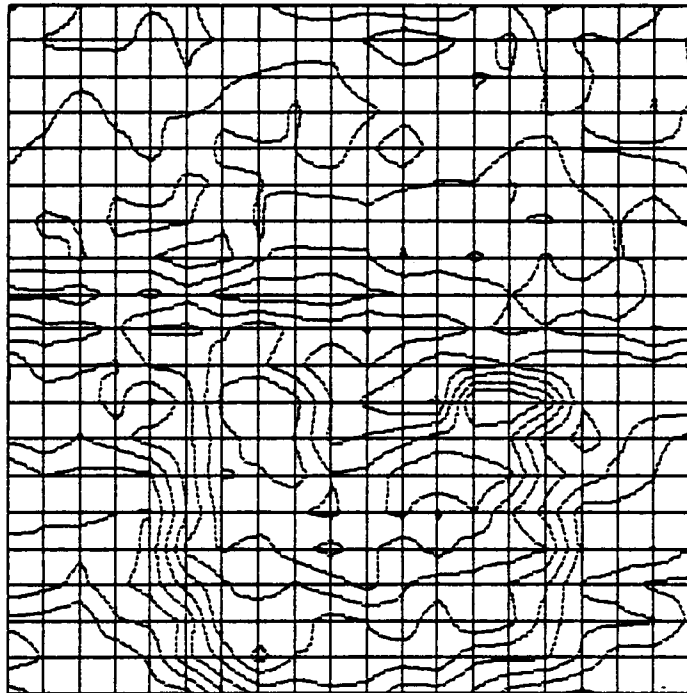
Figure 49. Contour Map of Radiance using Copper Specimen
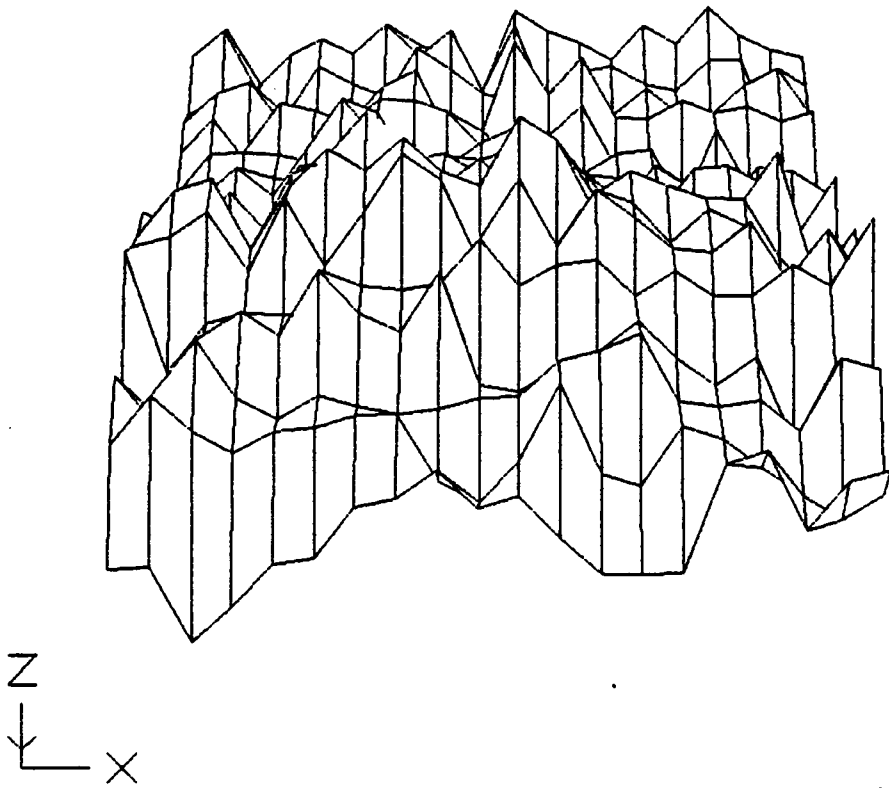
Figure 50. 3-D Representation of Radiance using Polyethylene Specimen (view 1)

Z

Y
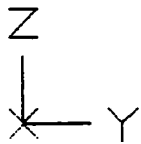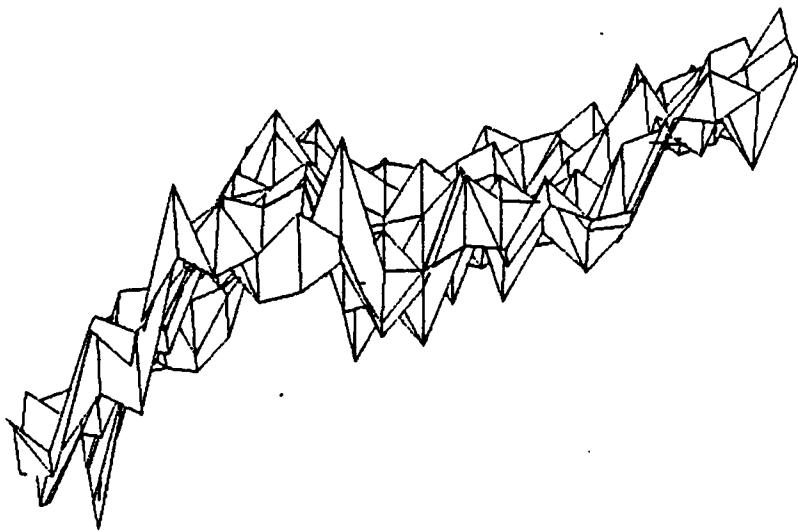
Figure 51. 3-D Representation of Radiance using Polyethylene Specimen (view 2)
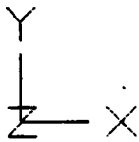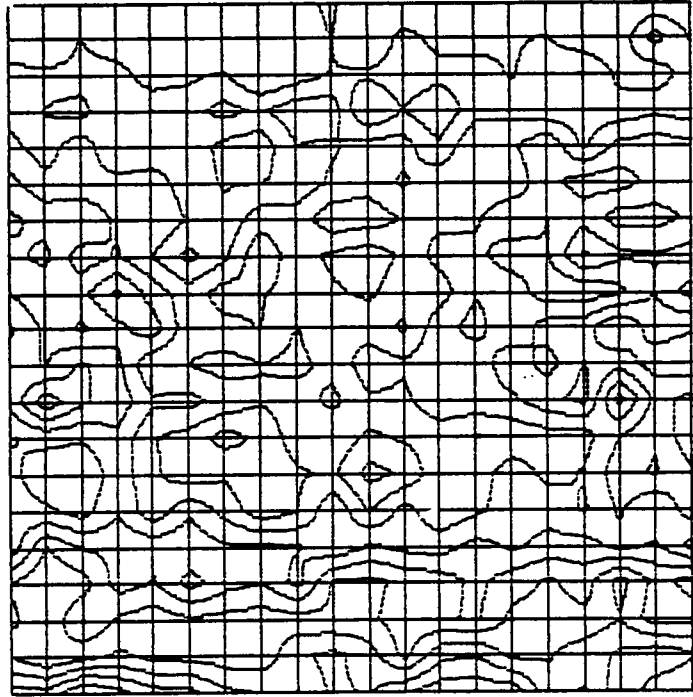
Figure 52. Contour Map of Radiance using Polyethylene Specimen
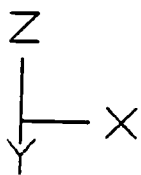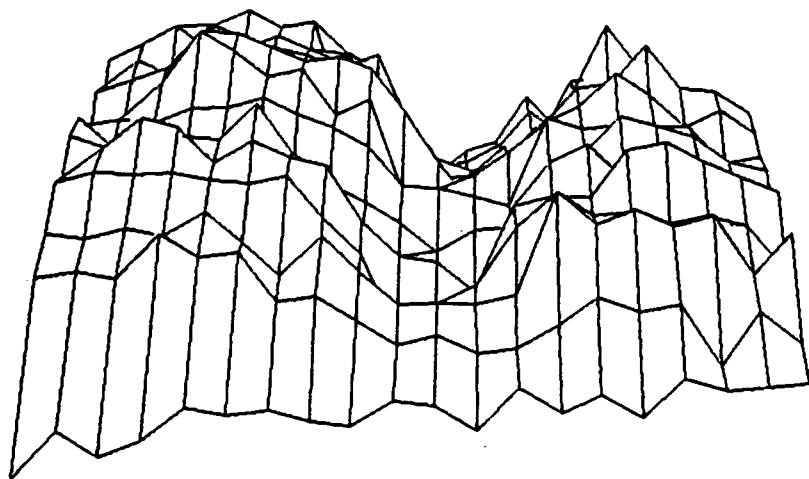
Figure 53. 3-D Representation of Radiance Using Split Copper Specimen (view 1)
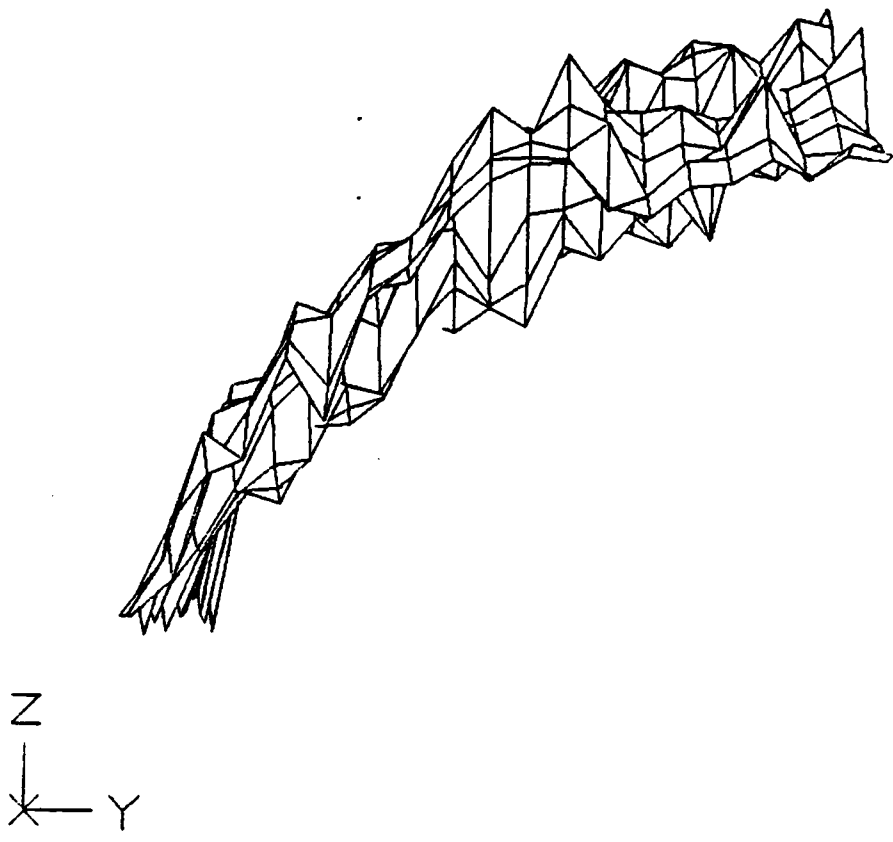
Figure 54. 3-D Representation of Radiance Using Split Copper Specimen (view 2)
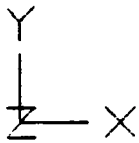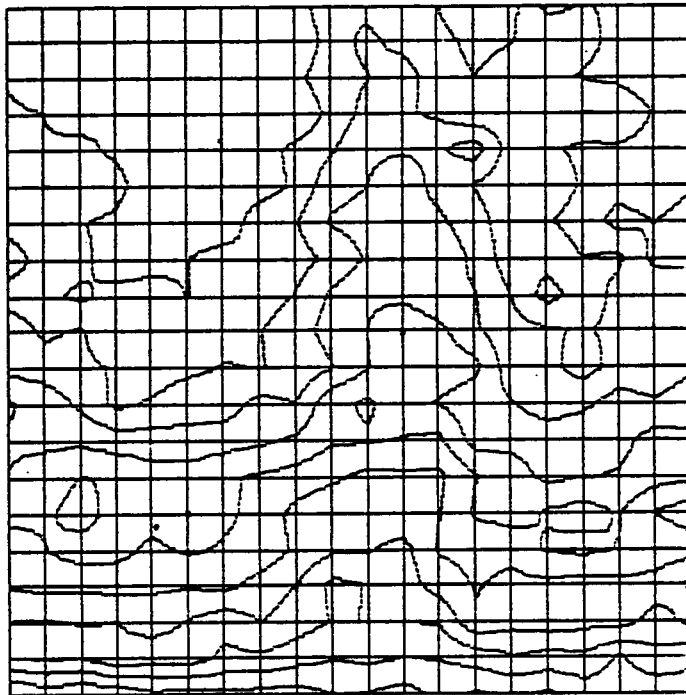
Figure 55. Contour Map of Radiance Using Split Copper Specimen

91

mined. If an emissivity map is generated for the region of contact, then this map can be easily coupled with the radiance map to generate accurate maps of the temperature at the interface.

Although the radiance mapping system seemed to be successful in generating radiance maps for the iron and the two copper systems--by showing a region of higher radiance over the region of contact--the maps generated for the silver and the polyethylene specimens were not as expected. In his work with a silver-on-sapphire system, Hollowell [36] found the radiance to be considerably high over the ragion of contact. But the measurements were made almost immediately after sliding began. In the present study, the radiance mapping took about 15 minutes--allowing enough time for oxide transfer to the disc. This could be a possible reason for the lack of high radiance over the region of contact.

5.2.2 Transient Measurements

5.2.2.1 Preliminary Experiment

The set-up shown in Fig. 56 was used to compare the signals generated by the AC/DC (hitherto referred to as the "AC" channel) and the DC channels in response to a fast thermal transient. The sapphire disc was covered with copper foil to prevent any IR radiation from passing through the disc. However there was one slit which allowed radiation to pass through. The slit allowed IR radiation to pass through the disc to the microscope for a very short duration--once every rotation of the disc. The microscope objective was focussed on the tip of a hot soldering gun (which was the source of IR radiation in this experiment). When the disc rotated, the microscope "saw" the target spot whenever the slit came between the two. For the rest of the time, the IR radiation from the soldering gun was blocked out by the copper foil. The duration of this transient radiation (caused by the alignment of the soldering gun, microscope, and the slit) depended on the speed of rotation of the disc, the width of the slit, and the radial distance of the target spot from the center of rotation of the disc.

The disc was rotated at 900 RPM and the tip of the soldering gun was placed just below the disc, at a distance of 1 cm from the axis of the shaft. The velocity with which the disc moved, under the microscope, was 94.25 cm/s. Various slit widths were used and the outputs from the DC and the AC channels were recorded. Table 2 shows the combination of parameters for the various tests. Figs. 57 through 62 show traces of the voltage outputs from the two channels for the different slit widths used.
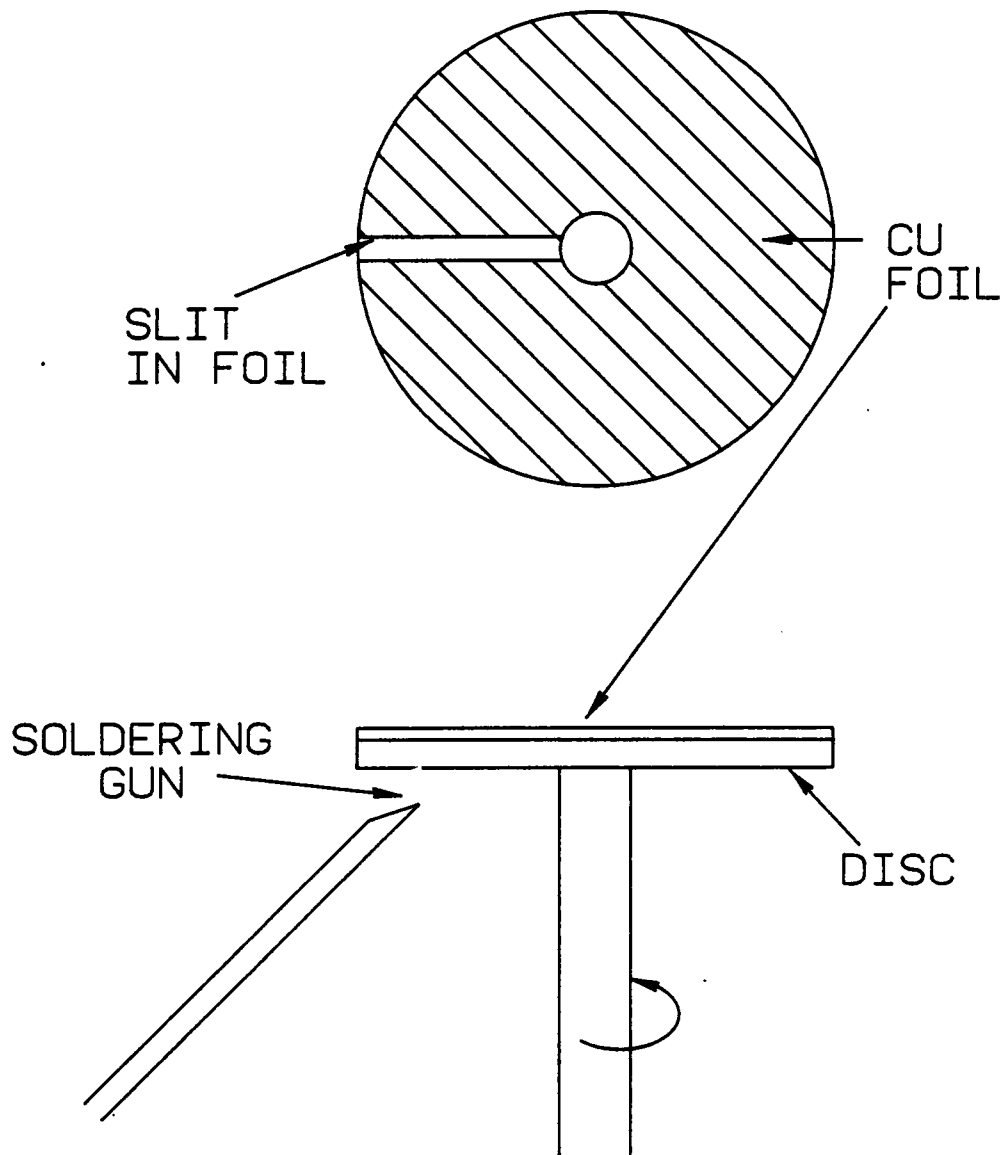
Figure 56. Set-Up for Testing the Transient Response

TABLE 2 – Test Conditions for Transient Measurements
(Preliminary Experiment)

TEST NO.	VELOCITY (cm/s)	SLIT WIDTH (mm)	DURATION OF PEAK (ms)
1	94.25	1.20	1.27
2	94.25	2.00	2.12
3	94.25	3.28	3.48
4	94.25	5.33	5.65
5	94.25	10.16	11.73
6	94.25	15.24	16.20

TIME
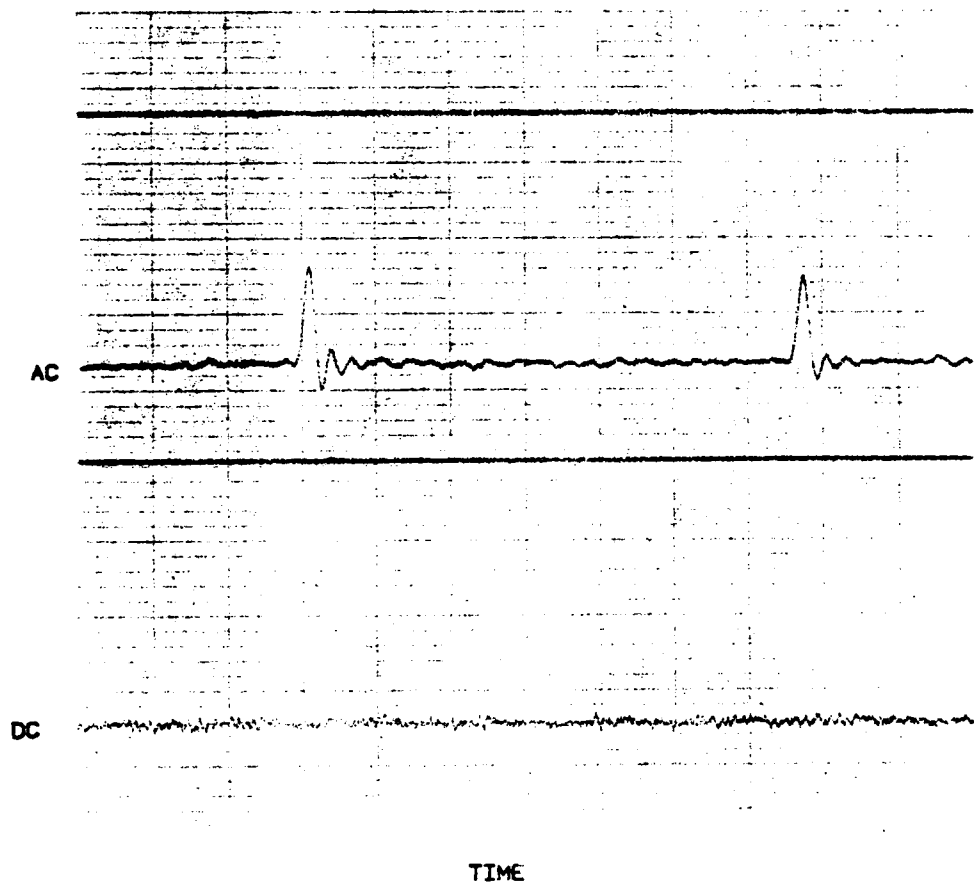
Figure 57. Transient Response (AC and DC)--Test 1
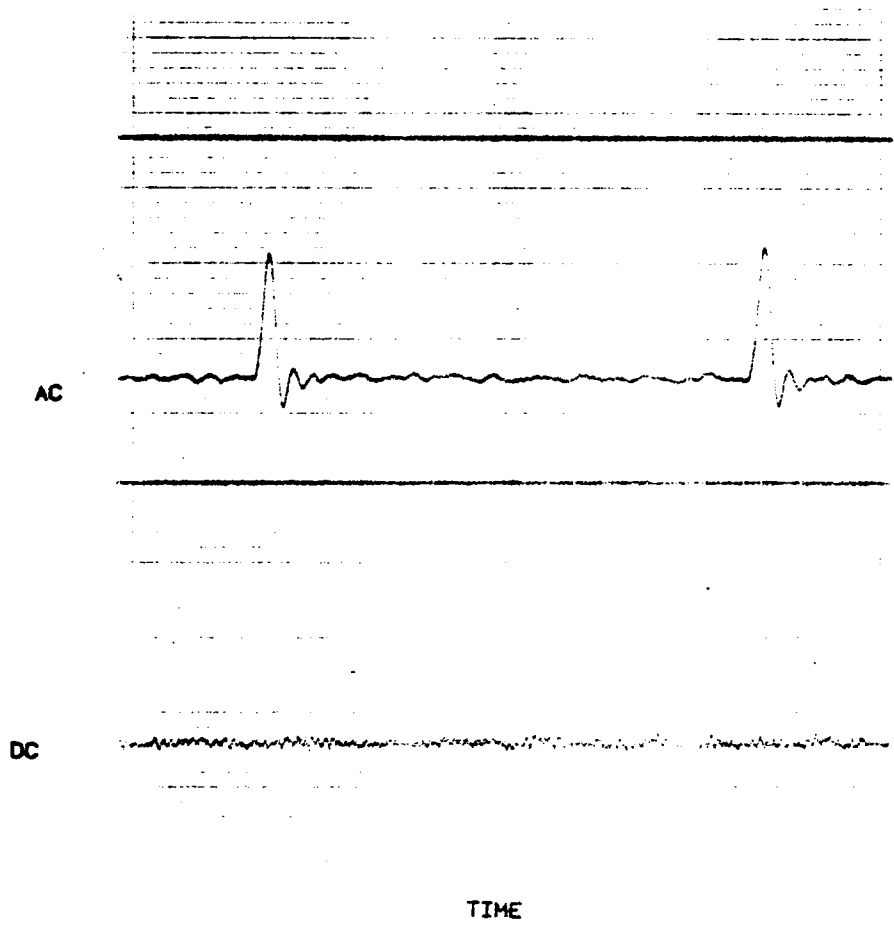
Figure 58. Transient Response (AC and DC)--Test 2

97
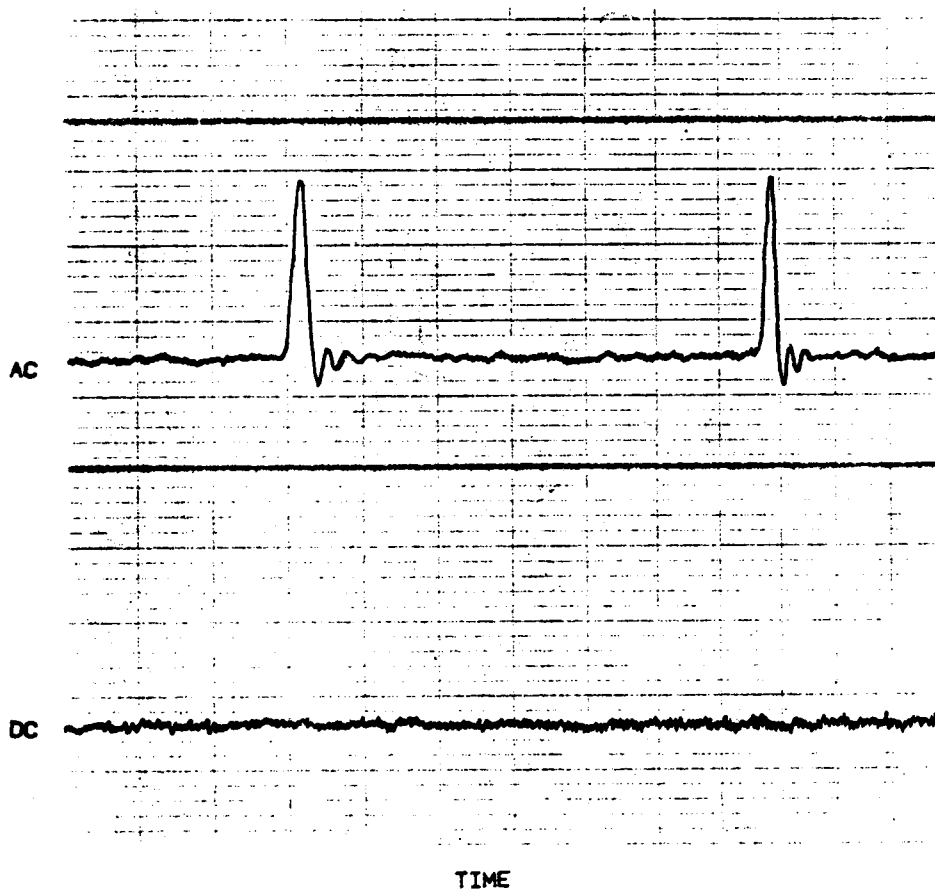
Figure 59. Transient Response (AC and DC)--Test 3
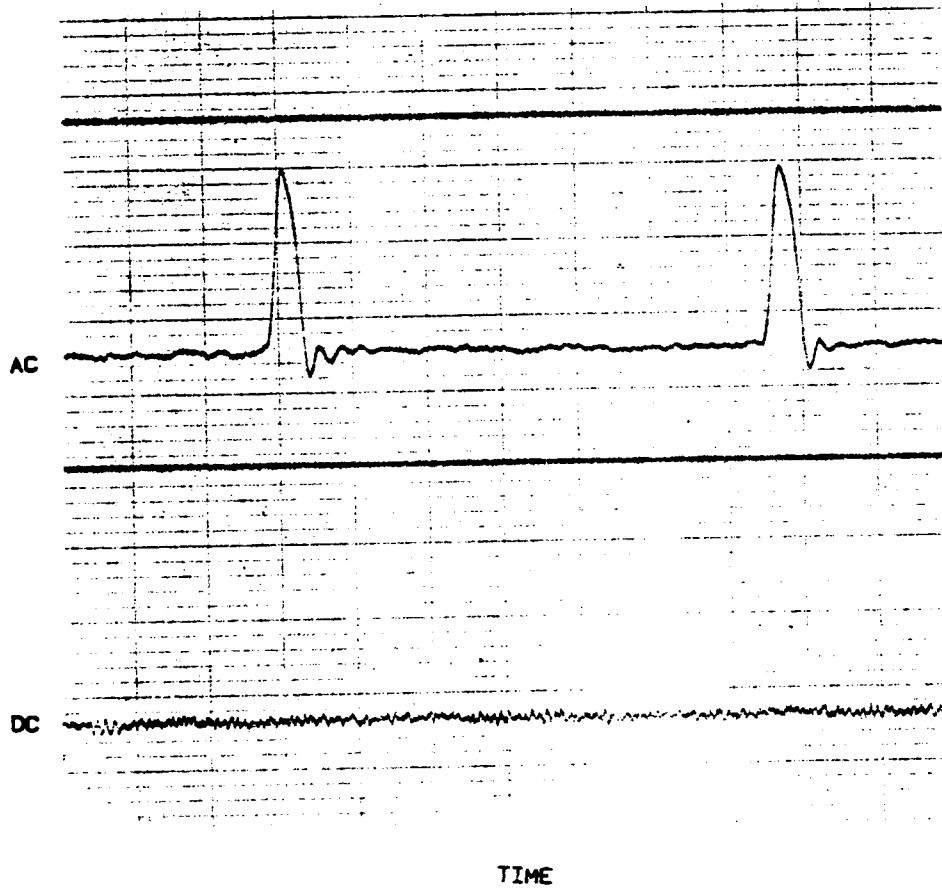
Figure 60. Transient Response (AC and DC)--Test 4

AC

DC

TIME
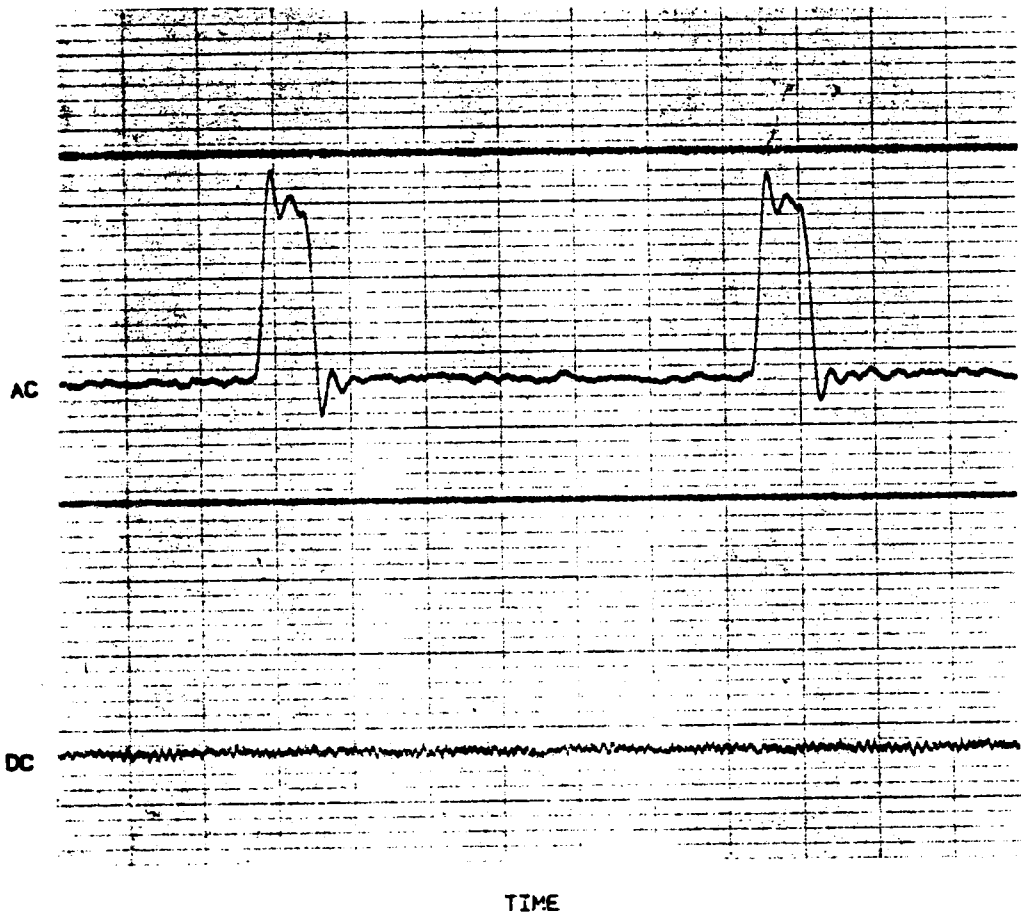
Figure 61. Transient Response (AC and DC)--Test 5
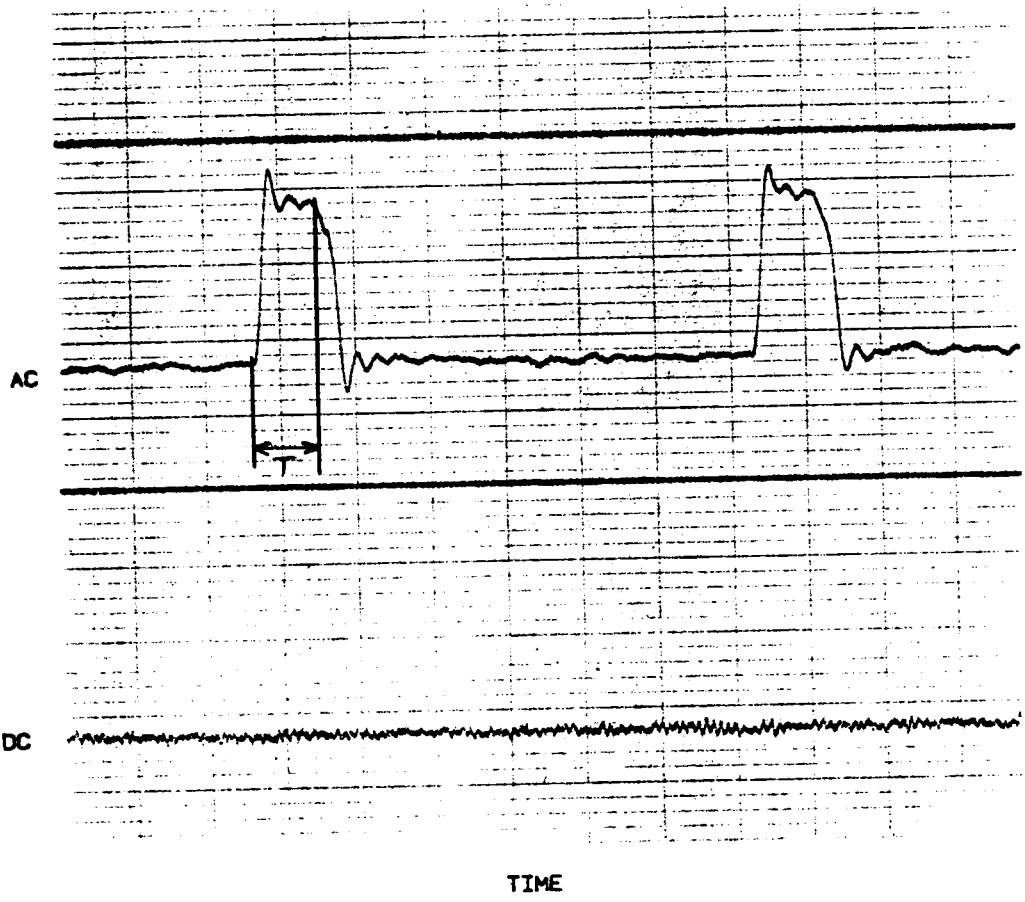
TIME

Figure 62. Transient Response (AC and DC)--Test 6

It is evident from the results of these experiments that the AC channel of the control unit was able to pick up and record the transient radiation whereas the DC channel was not able to do so. The time interval between the peaks was .067 s, which correctly indicated a frequency of 15 Hz (900 RPM). The durations of the peaks showing up on the output from the AC channel were measured, and then compared with the actual duration of the peaks (calculated from the slit width and velocity); the results are shown in Table 3.

The outputs shown in Figs. 57 to 62 were recorded using an Ultraviolet Oscillograph (frequency response of 2 Khz). When the first edge of the slit comes under the microscope, the IR detector sees a sudden jump in the radiance coming from the target spot. As the second edge of the slit comes under the microscope, the radiation from the soldering gun is abruptly cut off. Thus the transient peak can be expected to be a square pulse. The durations of these pulses for the various slits were calculated from the oscillograph outputs as shown in Fig. 62 (shown in the second column of Table 3).

It can be seen from Table 3 that the values of the peak durations calculated from the AC outputs are not equal to the values calculated from the actual slit width. Moreover, for narrow slits, the pulse reproduced by the oscillograph is not square in shape as expected. This could be due to the response limitations of the oscillograph. For wider slits, although the form of the pulse is as expected, the time duration of the pulse (calculated from the output) is much lower than the actual duration. The reason for this is not known.

It is important to note that the path of radiation from the soldering gun to the microscope is quite complex in nature. There is an intervening layer of air which could bring about multiple reflections and refractions of the IR radiation. The flow of radi-

102

TABLE 3 – Results of Transient Measurements
(Preliminary Experiment)

ACTUAL DURATION OF PEAK (ms)	DURATION OF PEAK (FROM AC OUTPUT) (ms)
1.27	1.50
2.12	1.90
3.48	2.80
5.65	3.00
11.73	6.70
16.20	9.10

ation must be thoroughly studied and understood before making any attempt to further explain the differences between the two columns of Table 3.

Another important feature to be noticed is the fact that the AC channel of the microscope does pick up the fast thermal transients whereas the DC channel does not. The signal from the DC channel passes through a 400 Hz low pass filter. The pulses from the target spot for the wider slits definitely fall within this range and it is surprising that the DC channel does not respond to them. The reason for this is not known and tests should be conducted to determine the true frequency response of the DC channel.

5.2.2.2 Sliding Systems

A special experiment was carried out with a sliding system to test and analyze the output from the AC channel and compare it with the output from the DC channel. An iron pin with a hemispherical head was used as the specimen and was loaded against the sapphire disc at a radial distance of 0.75 inch. The load applied on the specimen was 1N. The shaft was rotated at 900 RPM, giving a sliding speed of 0.18 m/s.

· The AC and DC outputs were connected to two different channels of a Honeywell FM Tape Recorder. The specimen was mounted against the disc and the microscope objective was focussed on the center of the region of contact. The recorder was then started and allowed to record the outputs from the microscope, without any sliding at the interface. The shaft motor was then turned on and and the interface was allowed to undergo sliding for some time. The microscope was then moved away from the region of contact and then moved back and forth to scan across the region of contact. After three such scans, the microscope was moved back to the center of the region of contact

and the motor was switched off. After allowing the interface to cool for some time, the tape recorder was stopped.

Fig. 63 shows the outputs from the DC and the AC channels of the microscope for the entire experiment. The DC output was fed into the tape recorder through an amplifier with a gain of 30X. The AC output was fed into the recorder directly without any amplification. Thus, the two traces shown in Fig. 63 cannot be compared with each other since they are not on the same scale. Some other factors (mentioned below) also had to be determined before comparing the two outputs.

The DC output comes through a 400 Hz low-pass filter and hence it is likely that the signal will be attenuated by this filter. In order to find this attenuation factor, the outputs from the AC and DC channels were compared. Since the only difference between the two is in the presence of the filter, the ratio of the two outputs was taken to be a measure of the filter attenuation factor. The microscope was focussed on the black body calibration source (at room temperature) and the output was zeroed. The black body radiation source was then heated to $100^{\circ}C$ and the outputs from the two channels of the microscope were recorded. While the DC channel gave an output of 0.14V, the AC channel gave an output of 0.26V. Thus, the filter attenuation factor was 7/13. Since all previous work with the microscope (including calibration) had been done with the DC channel, the output from the AC channel had to be multiplied by a factor of 7/13 before further processing.

The next instrument to be calibrated was the FM tape recorder. An input signal of 0.5V was fed into both the channels being used for this experiment and the recorded signal was played back. The AC channel returned 0.495V while the DC channel returned 0.44V. Thus, the AC output had to be multiplied by a factor of 0.5/0.495 while the DC
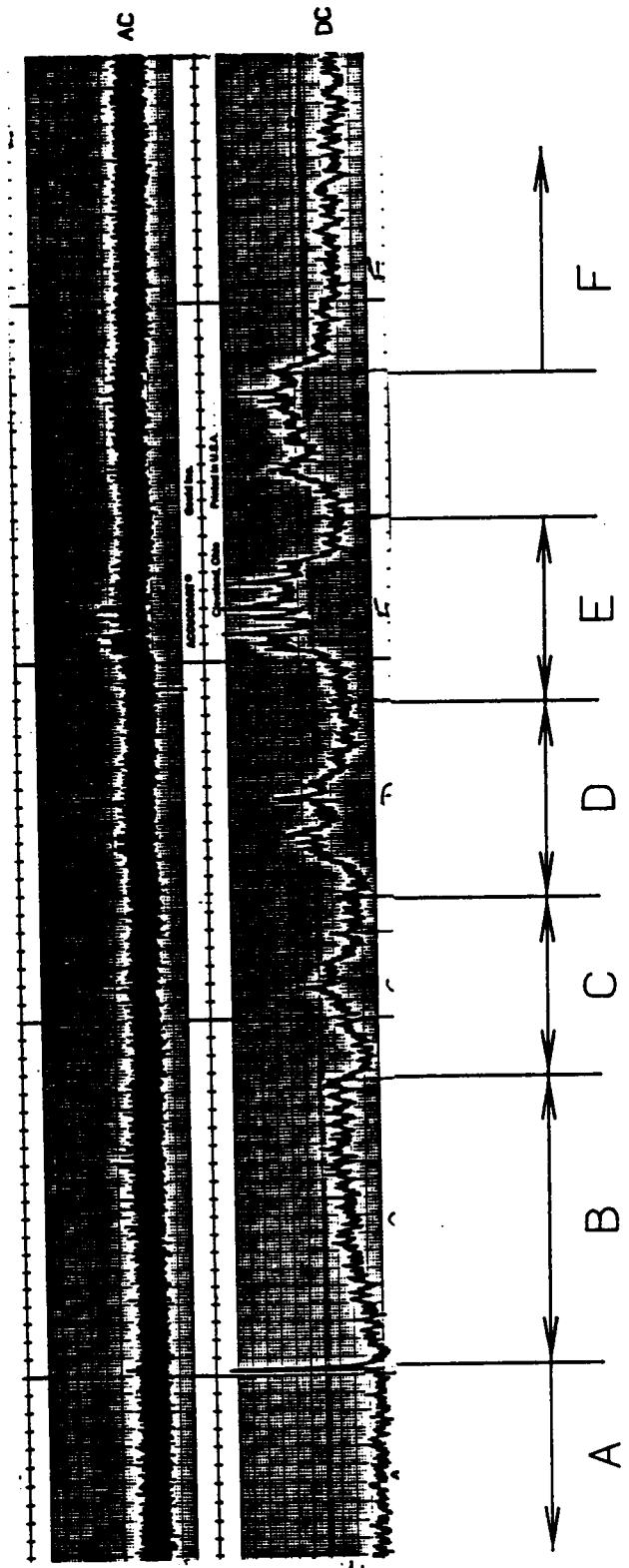
Figure 63. DC and AC Traces for the Iron-Sapphire Experiment

output had to be multiplied by a factor of 0.5/0.44 to account for the attenuation in the tape recorder. Because of the differences in the outputs from the two channels of the microscope and the gain in the amplifier used to record the DC output, the AC output had to be multiplied by a factor of 14.8 in order to bring it to the scale of the DC output shown in Fig. 63.

The two hard copy output instruments used in this experiment (a Gould Brush Chart Recorder and an Ultra Violet Oscillograph) were also calibrated and checked for accuracy. Fig. 63 shows the AC and the DC outputs, as recorded by the Brush chart recorder. Region "A" represents the time before sliding while region "B" represents the time after the motor was started and before the scanning began. Regions "C", "D" and "E" represent the three scans across the region of contact and region "F" represents the time after the motoᵢ was stopped.

The level of radiation in region "A" represents the radiation level at room temperature. When the motor was started, there was a large jump in the signal from the DC channel (point "AB" in Fig. 63). This can be attributed to electrical noise from the motor switch.

In region "B", the radiance increased steadily with time, as expected. The radiance level dropped when the microscope was moved out of the region of contact, as shown by the few initial seconds of region "C". Then, as the microscope was moved across the region of contact, the radiance level increased and then went down again. The other two scans across the region of contact (shown by the regions "D" and "E") also show higher radiances over the contact area. Moreover, the level of radiance over the region of contact also increased with time (e.g., the radiance in region "D" is higher than that in

region "C"). After the motor was stopped, the sliding stopped and the radiance level dropped as the interface cooled down.

It can be seen that in the region "E", there are a few short duration peaks (or high radiance levels). Although these peaks appear on both the DC and AC channels, they seem to be attenuated in the DC channel. This can be attributed to the fact that the DC output comes through the 400 Hz filter which would tend to cut down transient peaks. The chart recorder used for this output had a frequency response limit of 80 Hz and this could have attenuated the signals (in both the AC and DC outputs) to some extent.

In order to minimize this attenuation, an Ultraviolet Oscillograph, with a higher frequency response (2 kHz), was used to get a hard copy of the region "E". This output is shown in Fig. 64, with the AC and DC channel outputs shown on similar scales (the AC output was amplified with a gain of 15 X). It can be seen quite easily from this figure, that in AC output the peaks are much higher than in the DC output.

The peak voltage at point "A", shown in Fig. 64, was measured for both the DC and AC outputs and converted to the Effective Black Body Radiance, using the conversion technique described by Moyer [9] . A surface emissivity of 0.45 was used for the conversion. These radiance values were then converted to temperatures using the conversion charts in Ref [32] . The surface temperature indicated by the point "A" on the AC output is 75°C , whereas the DC channel indicated a surface temperature of 35°C . Thus, it is quite obvious that some information is being lost by the DC channel, as far as fast thermal transients are concerned.
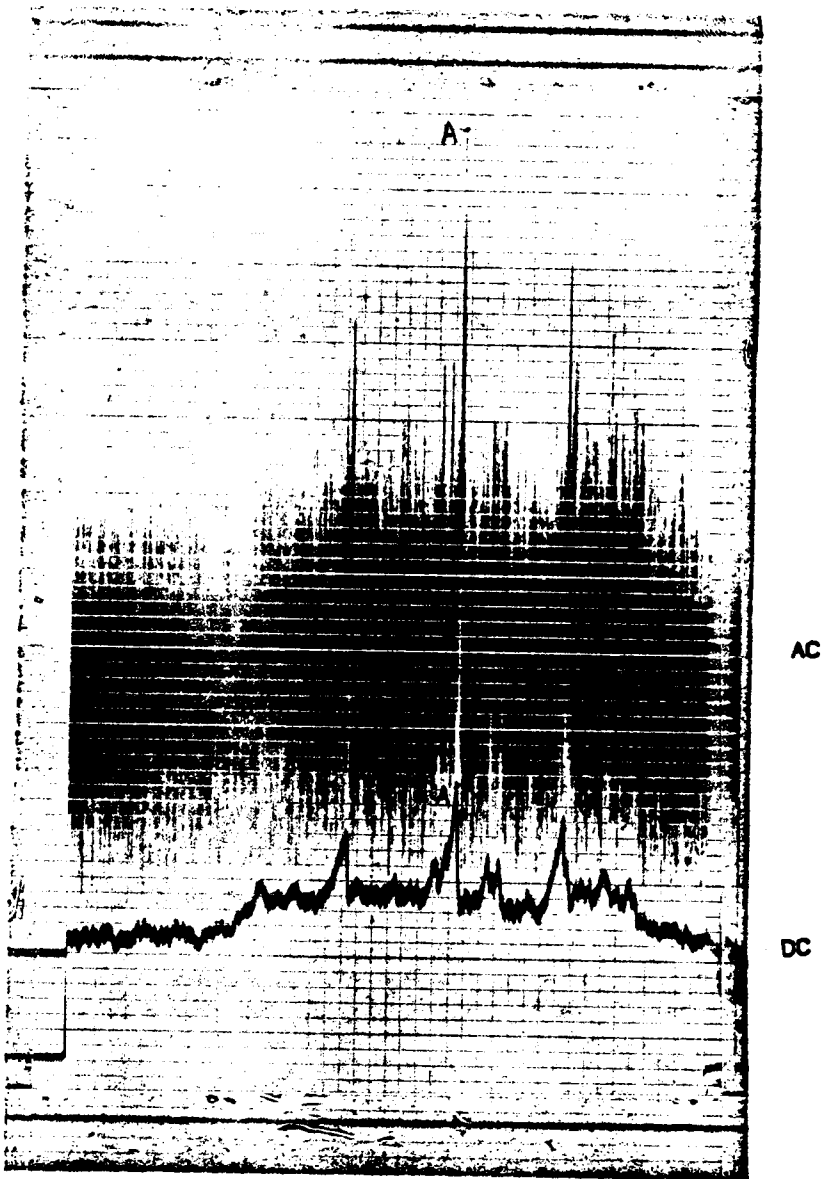
Figure 64. AC and DC Outputs as Recorded by the UV Oscillograph

The surface temperature value of 35°C compares well with the peak temperature of 37°C reported by Moyer [9] for a similar experiment. But the value of 75°C calculated from the AC channel output demonstrates the utility of using the AC channel for measuring peak temperatures.

The signals (from the AC channel) recorded on tape can be fed back into a digital system (e.g., the data acquisition system used for radiance mapping) and the peaks showing up on the AC channel can be further studied for other characteristics (e.g., duration of the peaks, etc.). Samples of signals can also be captured by the data acquisition system and treated to determine various statistical parameters.

Some samples of signals from the AC channel were taken (using the data acquisition system) for the other sliding systems--Cu, Ag, and polyethylene on sapphire. These voltage samples were then converted to effective black body radiance by using a calibration factor and an assumed constant emissivity value. The surface temperature is directly proportional to the fourth root of this effective radiance. Thus, the fourth root of the effective radiance was plotted against time (Ag and polyethylene specimens) (Figs. 65 to 68). In these figures, the Y-axis does not represent the actual temperature, but a variation of the surface temperature, i.e., the Y values in these plots are directly proportional to the surface temperatures.

The temperature fluctuations for the Ag specimen seem to be much more rapid than those for the polyethylene specimen. For a metal-on-sapphire system, the friction at the interface is higher than that in a polymer-on-sapphire system. Thus, the heat generated at the interface can be expected to be higher for a metallic specimen. Moreover, the true area of contact is smaller surface temperatures can be expected to be higher. A combi-
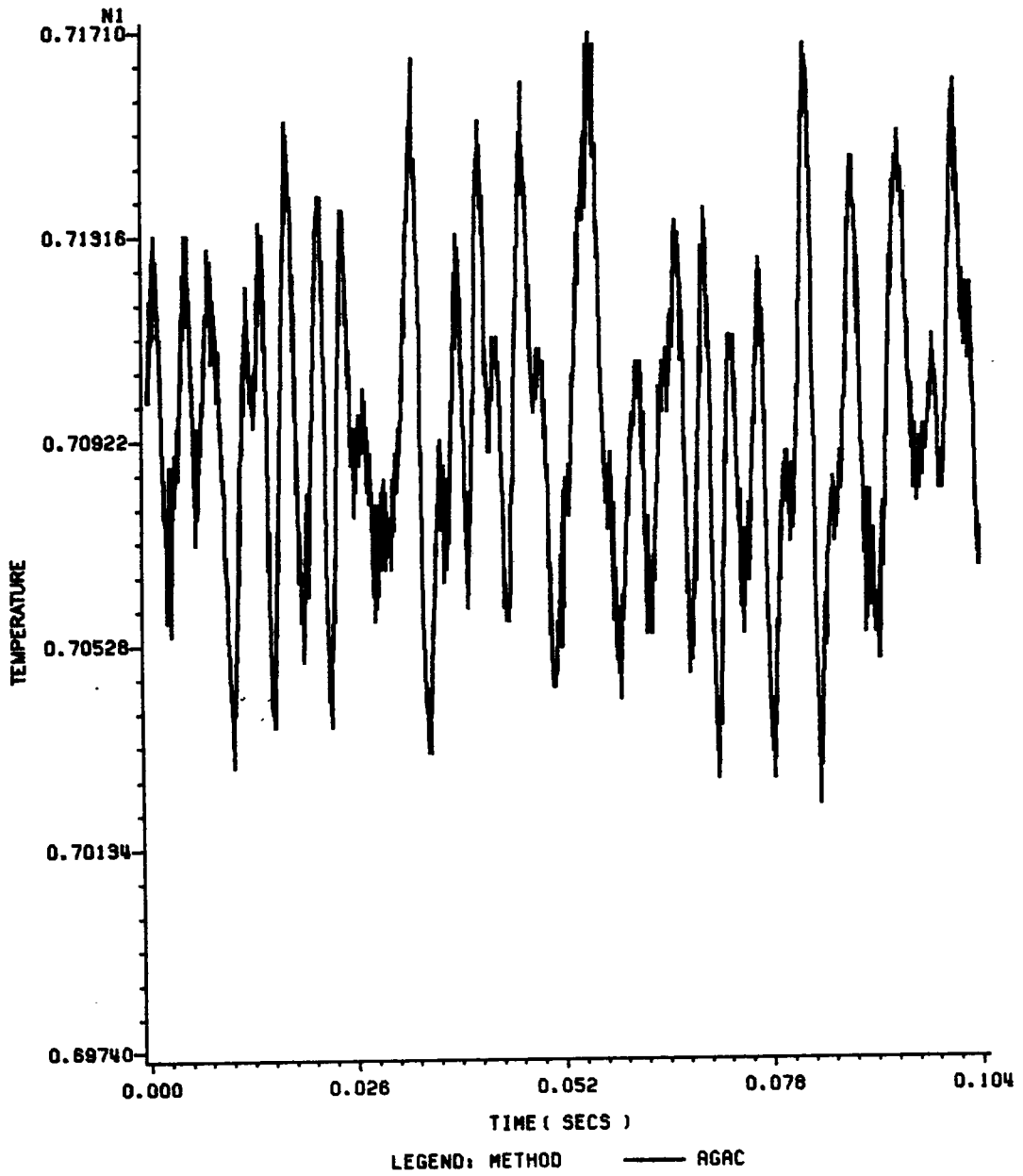
Figure 65. AC Sample for Ag Specimen--Sample 1
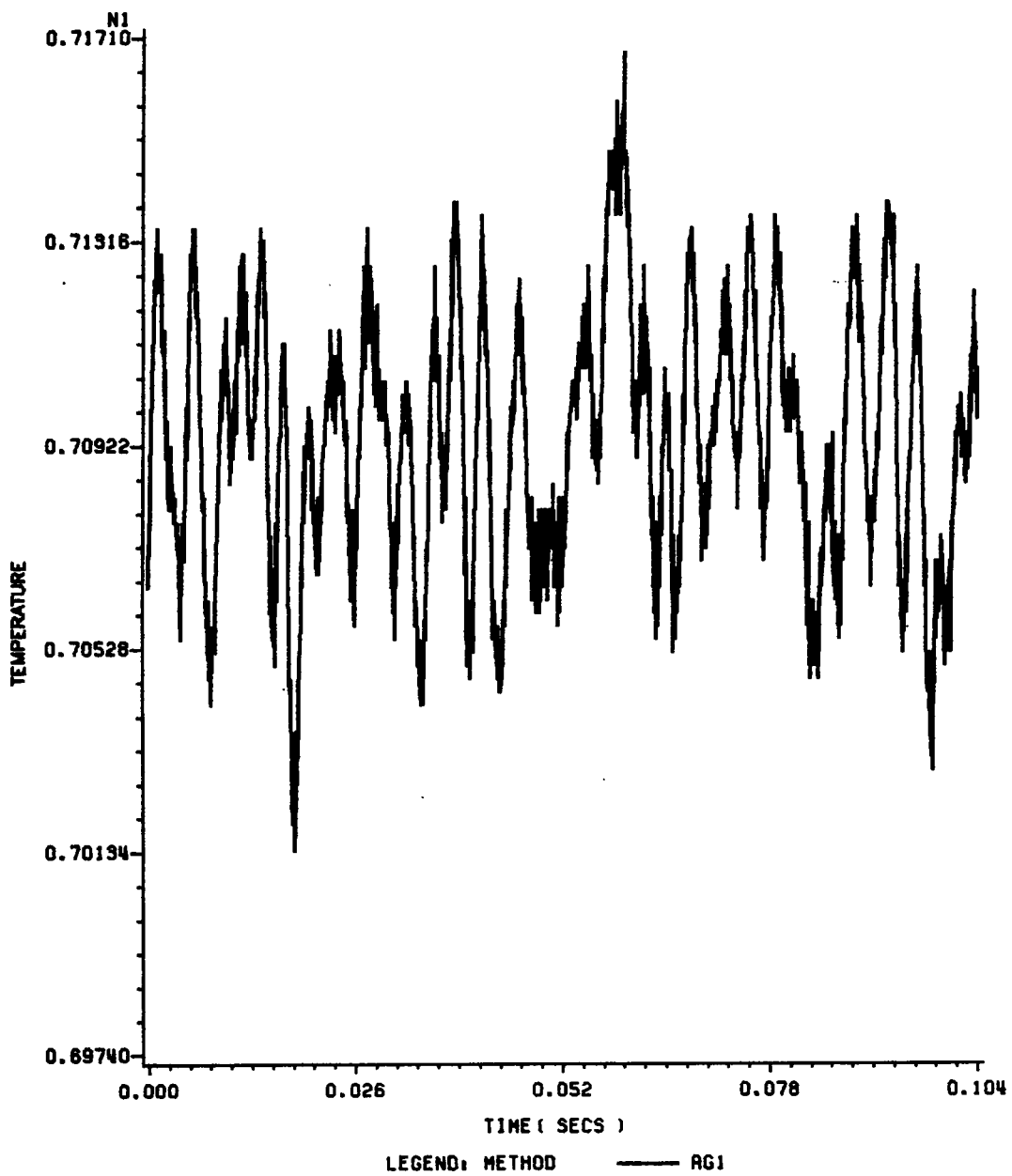
Figure 66. AC Sample for Ag Specimen--Sample 2
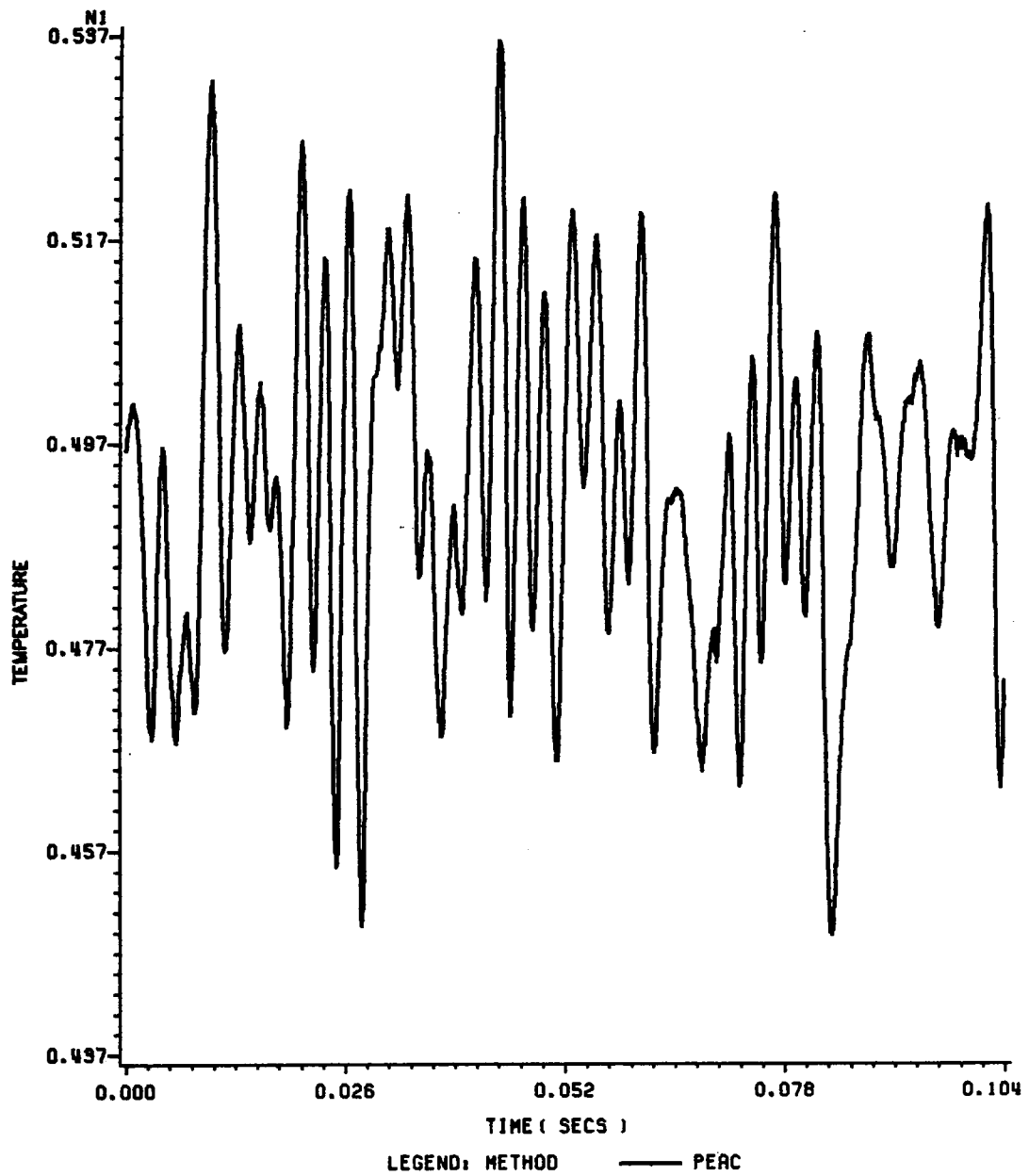
Figure 67. AC Sample for Polyethylene Specimen--Sample 1
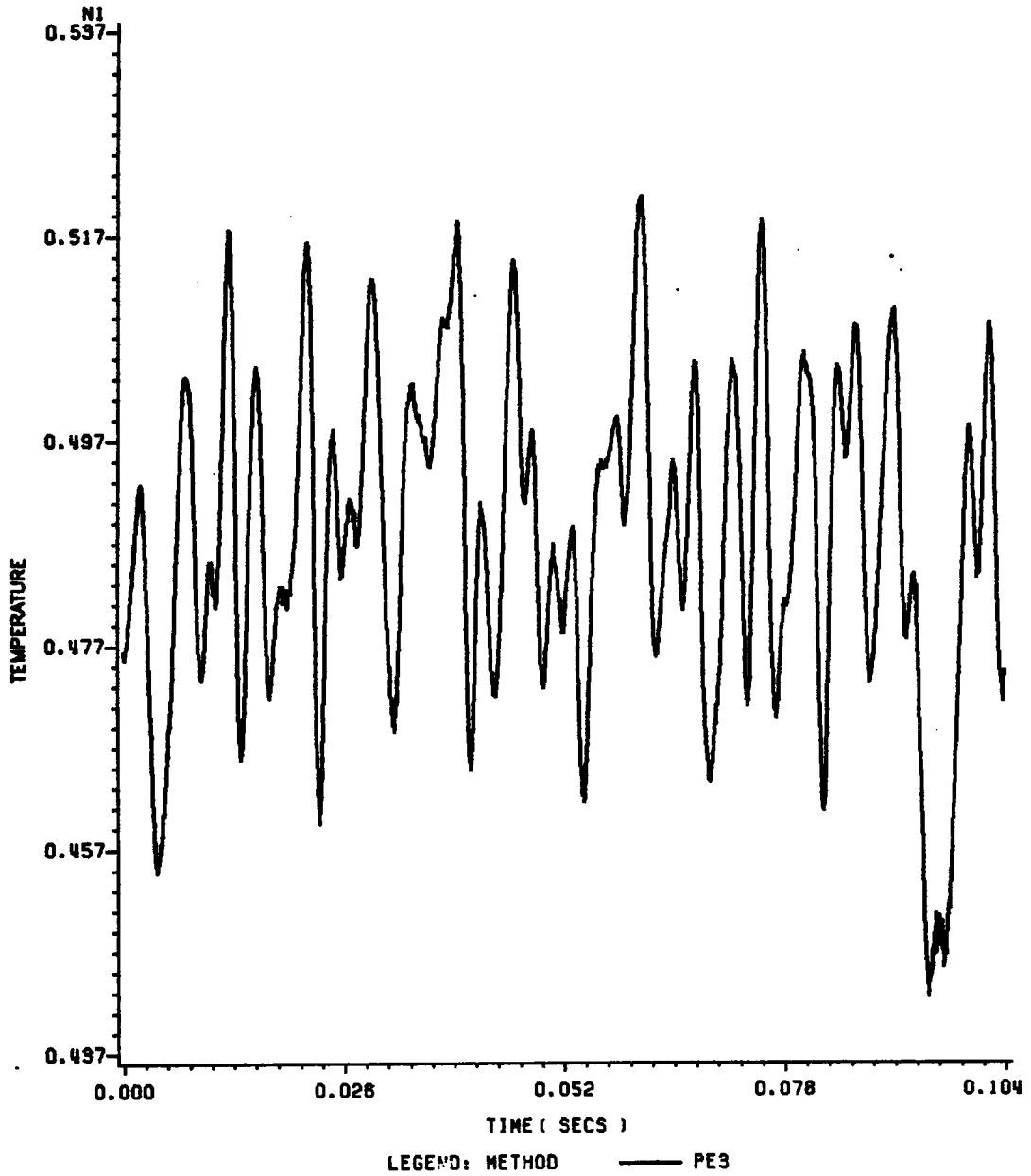
Figure 68. AC Sample for Polyethylene Specimen--Sample 2

114

nation of the above two factors could be a possible explanation for the presence of sharp peaks in the radiance from the surface of the silver specimen.

These samples of the signals were Fourier-transformed to find the frequency distributions. These distributions are shown in Fig. 69 to 74. This is just an example of how the data acquisition system can be used to treat samples taken from data on tape. Most of the predominant frequencies in these plots are below 400 Hz. But that does not imply that higher frequency thermal transients are non-existent. There might be some very fast thermal transients which do not occur often enough to be revealed on the frequency plots.

Another important feature of such experiments is that the data can be recorded on magnetic tape using the FM tape recorder, using a high tape speed; the recorded data can be played back to the data acquisition system at a much slower speed, effectively improving the frequency response of the data acquisition system.

It should be noted, however, that the samples taken by the computer are of very short duration and thus cannot be taken to be "typical" signals for the experiment. In order to increase the size of the samples, either continuous successive samples should be taken or the computer memory should be increased to allow the user to take large samples of signals.
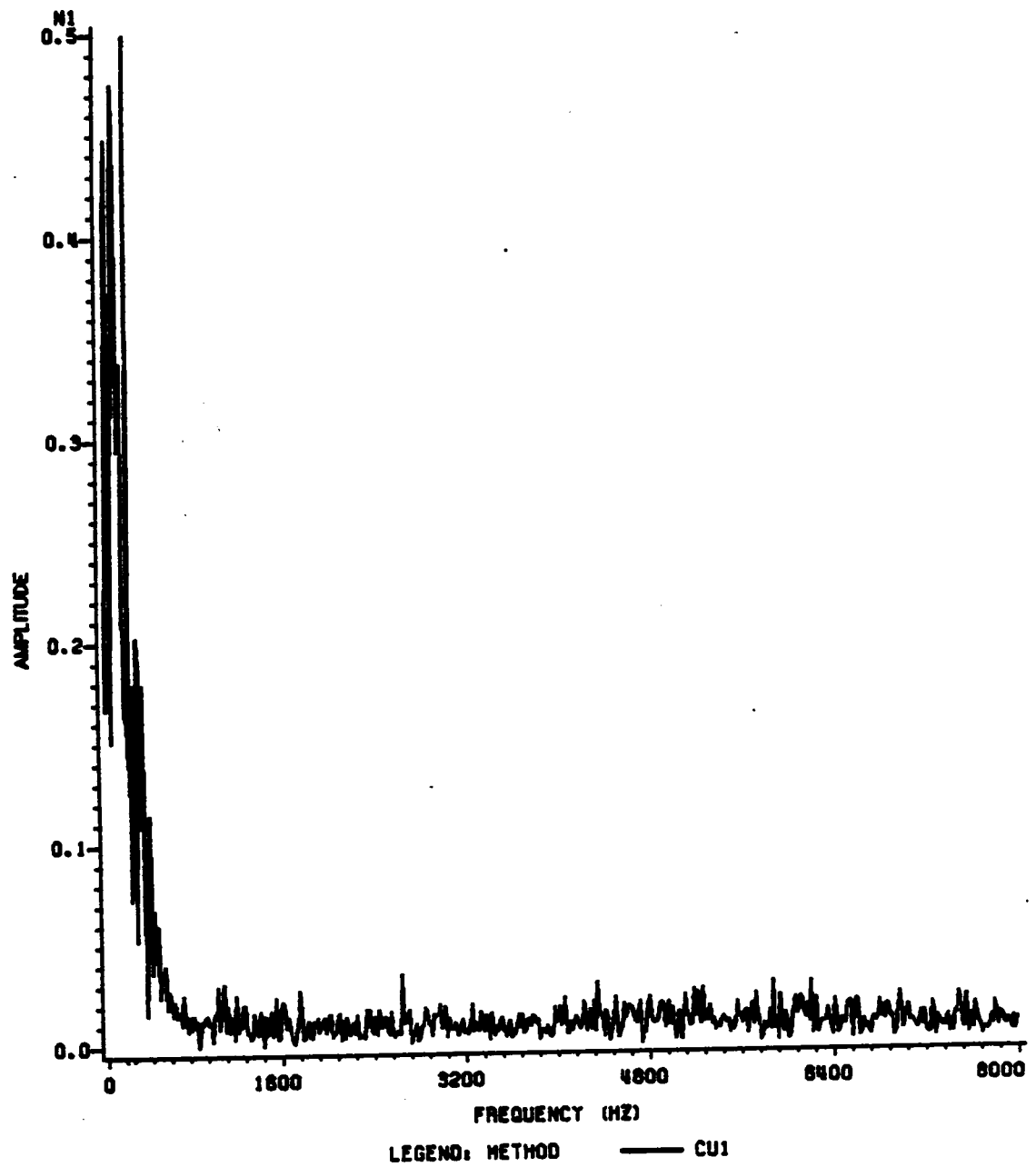
Figure 69. Frequency Distribution of AC Sample for Cu Specimen--Sample 1
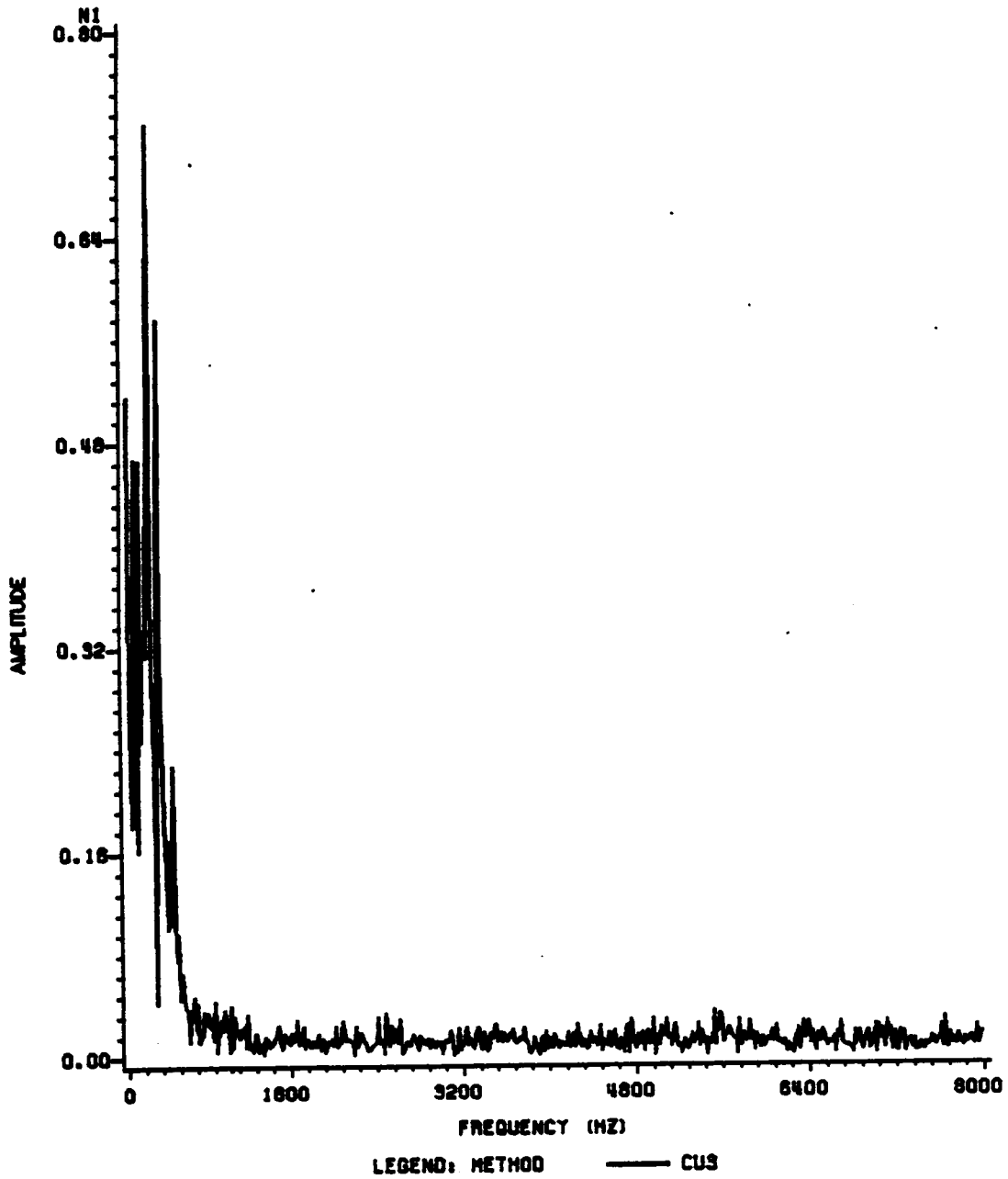
Figure 70. Frequency Distribution of AC Sample for Cu Specimen--Sample 2
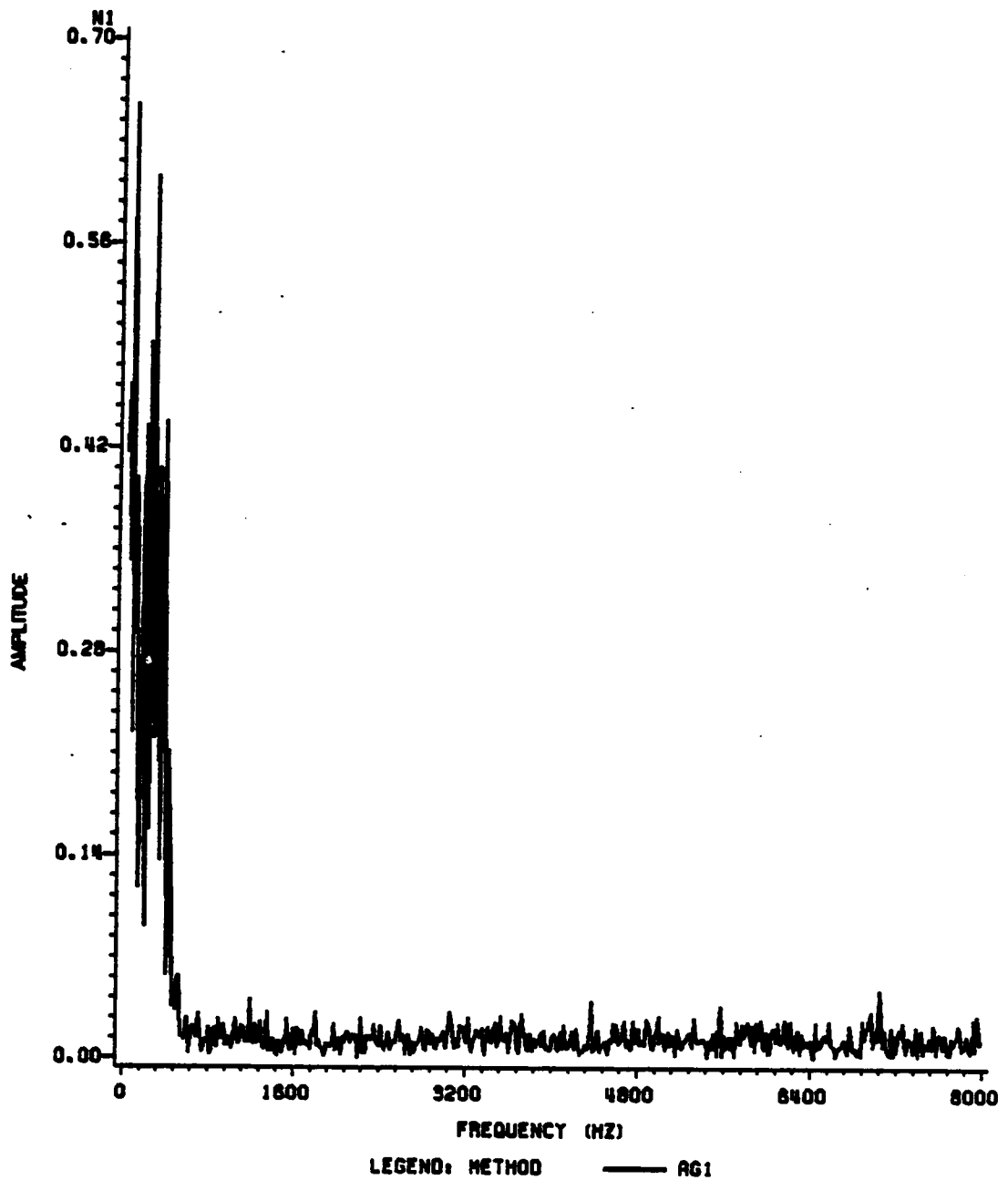
Figure 71. Frequency Distribution of AC Sample for Ag Specimen--Sample 1
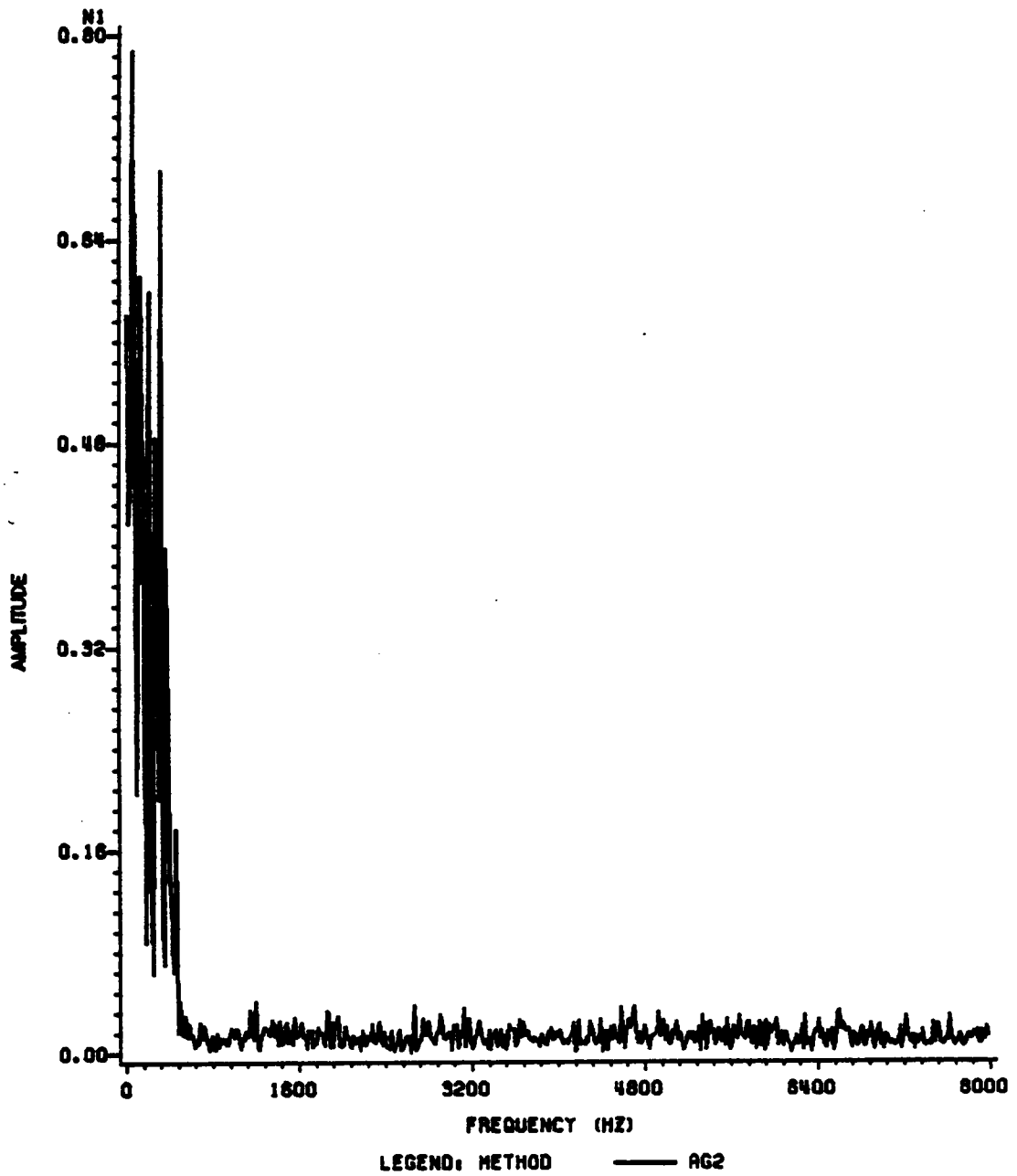
Figure 72. Frequency Distribution of AC Sample for Ag Specimen--Sample 2
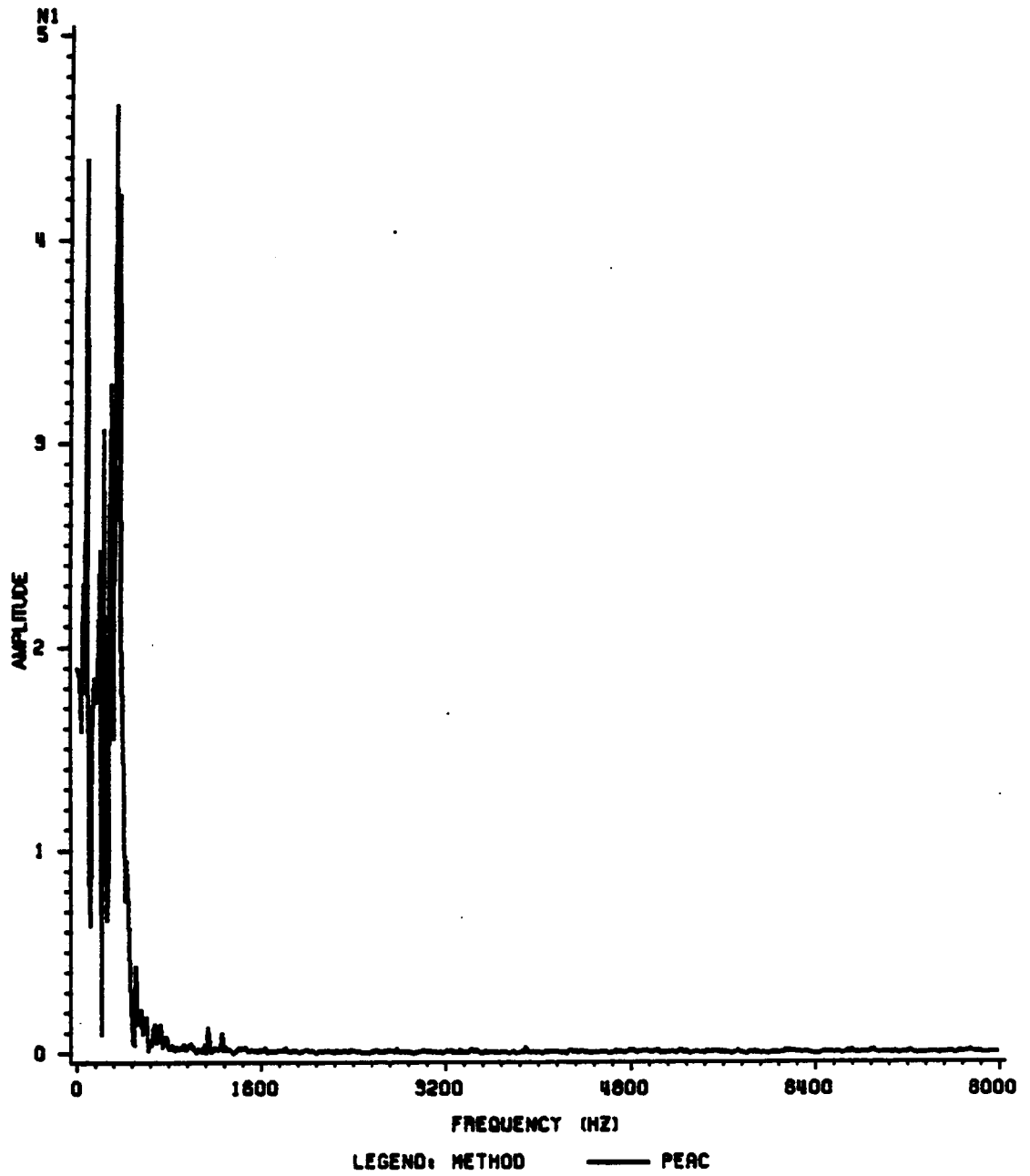
Figure 73. Frequency Distribution of AC Sample for Polyethylene Specimen--Sample 1
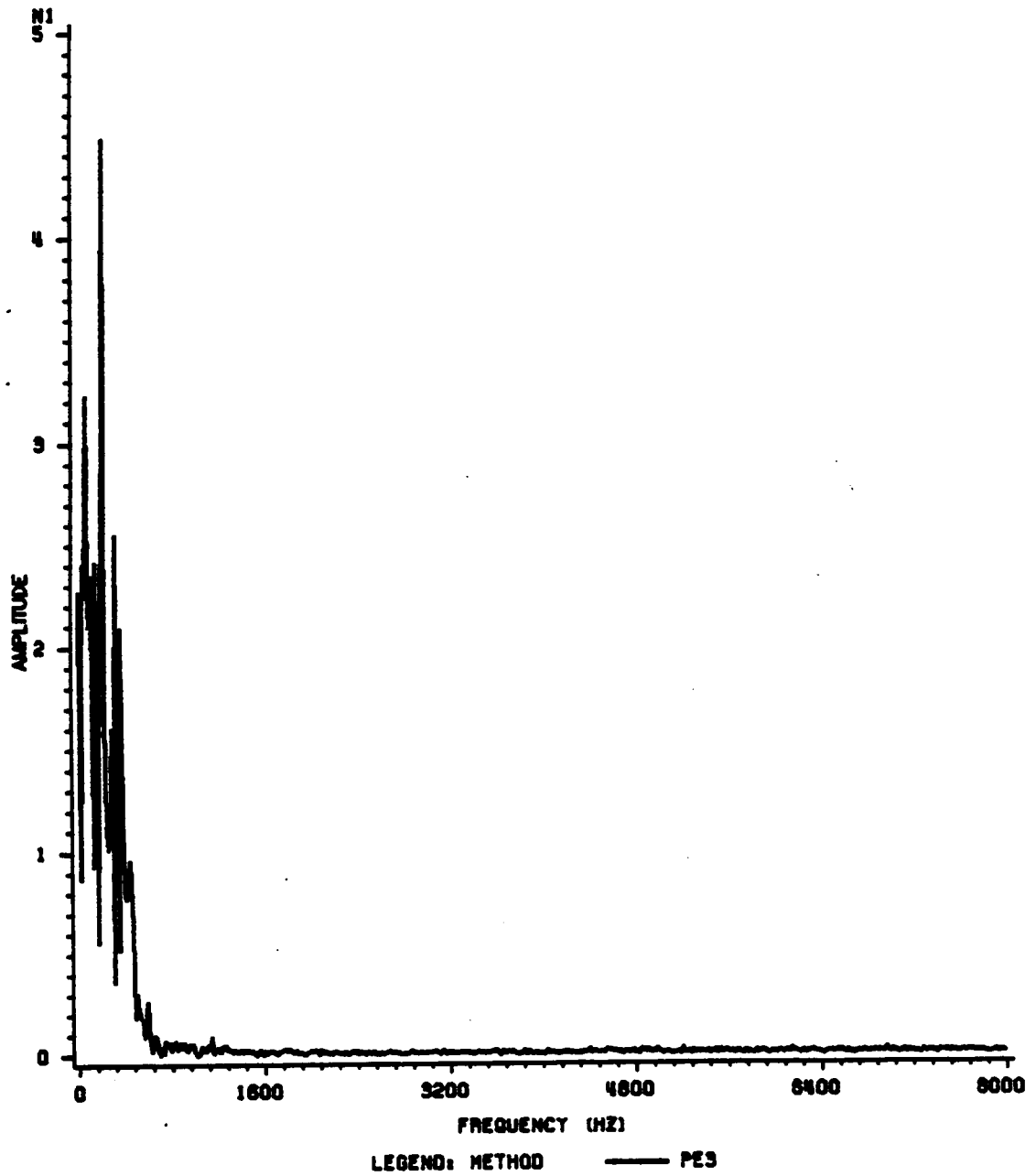
Figure 74. Frequency Distribution of AC Sample for Polyethylene Specimen--Sample 2

6. Comparison of the Systems: A Summary

The data from the Talysurf was successfully used to generate 3-D maps of rough surfaces. The viewing techniques used were very sophisticated. A ZTL DMS 5003 FFT machine was used to digitize the data from the Talysurf and a data acquisition system was developed for surface temperature studies. The data acquisition system used for surface temperature studies can also be used to digitize the Talysurf data.

The computerized data acquisition system was essentially an addition to the IR microscope system which had been used before. In the previous system, the signals from the microscope and its accessories were fed into an FM tape recorder and then reproduced using chart recorders. With the addition of the data acquisition system, the signals are fed into a computer either directly (e.g., in the case of radiance mapping), or through an FM tape recorder (e.g., in transient measurements) (Fig. 75).

In the previous system, the frequency response depended on the type of chart recorder used. However, frequency response of the system was not of much importance since all the studies in the past involved only the DC channel of the microscope. The frequency response of a digital system depends on the digitizing rate. This particular
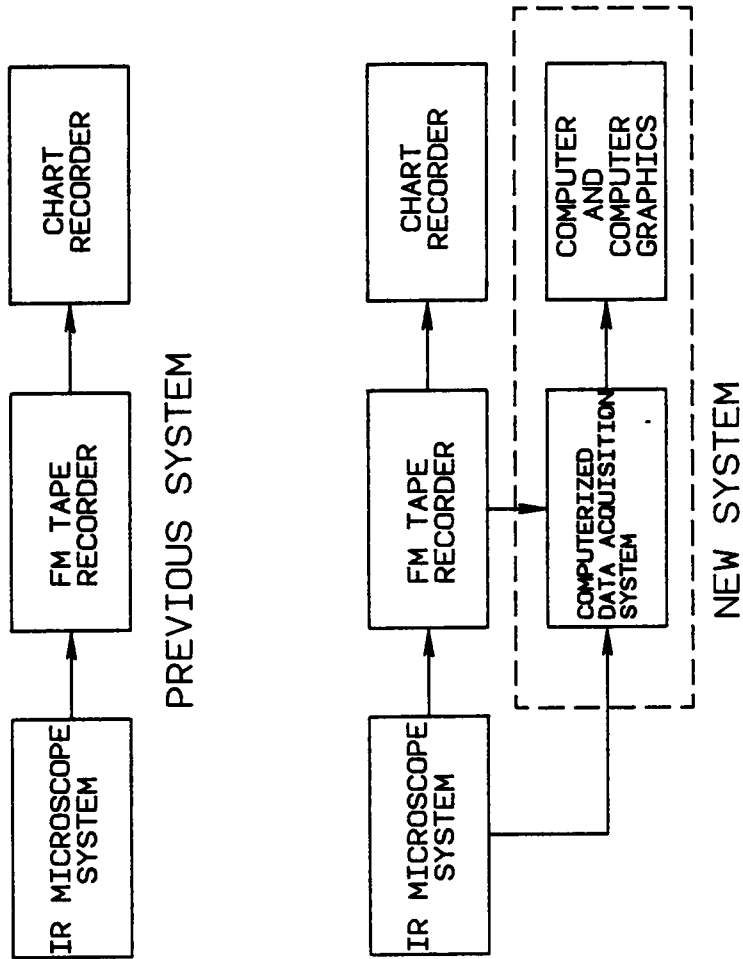
Figure 75. The IR Measurement Systems--Previous System and the Computerized System

digital system is capable of digitizing at the rate of 125 microseconds/sample--which implies that signals with frequencies higher than approximately 2 KHz will not be properly reproduced. This limitation can be overcome by recording the data on FM tape, using a very high tape speed, and then playing back the tape to the data acquisition system using a very low tape speed.

The resolution of the computerized system is 6 microvolts whereas in the previous system the resolution was limited by the chart recorder and by human factors (since the data was visually read off the chart recorder outputs). Hence, the data collected by the data acquisition system is more accurate.

In the past, the IR microscope had been used to generate radiance and temperature maps. The region of interest was scanned very fast and the data was stored on FM tape. This data was then reproduced using chart recorders and radiance maps were generated by picking off X and Y values and cross plotting them against radiance. This was a very time-consuming and laborious process. With the help of the data acquisition system, picking off the radiance values for radiance maps is semi-automatic (since the microscope is still moved manually) and effortless. However, the time taken to scan the region of interest is very long and the maps generated represent radiance variation not only as a function of position, but also as a function of time.

The conversion of radiance data to temperature levels [8,9] was very involved but accurate in the previous system. However, conversion of complex radiance data to temperature levels was almost impossible since all the data was in analog form. The addition of the data acquisition system makes possible the conversion of analog data to digital data. The previous techniques can then be easily used to convert complex radi-

ance data (digital) to temperature levels. Moreover, the digitized data can be analyzed statistically--e.g., frequency analysis.

A major limitation of the computerized system is the fact that long continuous samples of signals can not be taken because of computer-memory limitations; the longest continuous sampling time is 2.93 seconds. In the previous system, data from an experiment could be fed into the FM tape recorder for a long time (even up to 30 minutes) and then played back into chart recorders. Although the data can still be continuously fed into the tape recorder, the size of digitized samples is very limited.

A comparison of the capabilities of the previous system and the new computerized system is summarized in Table 4.

Table 4. Old System vs. New System for IR Measurements

CRITERION	PREVIOUS SYSTEM	NEW SYSTEM
Frequency Response	Dependent on the chart recorder used	About 2 Khz
Resolution	Limited by the resolution of the chart recorder and by human factors	6 microvolts
Accuracy	Data read from charts-- accuracy limited by eye estimates	No human errors involved
Radiance Mapping		
a. Scanning Speed	Very fast--a few minutes	Very slow--e.g., 15 minutes for 10 scan lines
b. Time for generating radiance maps	Very long--a few hours	Very short--a few seconds
c. Applying viewing transformations on 3-D radiance plots	Not possible	Simple and fast
Statistical treatment of complex data	Extremely difficult	Quite simple
Conversion of radiance data to temperature	Very accurate and involved --but very difficult for complex data	Can be coupled with the previous system for the conversion of complex data
Sampling time	Almost unlimited	Limited by the computer. memory

7. Conclusions

In the data acquisition systems discussed in this thesis, surface temperature measurements were centered around a Barnes Infrared Radiometric microscope. The sliding system consisted of a specimen (in the form of a pin or a sphere) loaded against a rotating, optically flat sapphire disk. Surface topography measurements were made with a Talysurf 4 Profilometer. 3-D computer graphics was used for viewing the data from the experiments.

The conclusions from this investigation are as follows : -

1. A data acquisition system was successfully coupled with the infrared microscope and its accessories to obtain radiance data from the area of contact of the sliding system.

2. Radiance distribution over the area of contact was successfully measured and computer graphics was used to display the results on a graphics monitor.

3. The "AC" or "Transient" channel of the infrared microscope was tested and used to study thermal transients. It was found to be functioning properly.

4. A comparison of the signals from the "AC" and the "DC" channels of the microscope showed that the "AC" channel captures more information than the "DC" channel when studying fast thermal transients.

5. The utility of the "AC" channel in measuring thermal transients was demonstrated with the help of some preliminary experiments and a sliding experiment (Fe-on-sapphire system).

6. The radiance data from the "AC" channel revealed large fluctuations which are not so prominent in the signals from the "DC" channel. These peaks indicate temperatures much higher than those indicated by the peaks in the signals from the "DC" channel.

7. Frequency analysis was performed on some samples of signals from the "AC" channel to demonstrate the the statistical analyses capabilities of the system.

8. The Talysurf 4 was successfully coupled with a digital computer to generate information about rough surfaces in three dimensions.

9. 3-D models of rough surfaces were generated from the data from the Talysurf 4, and MOVIE.BYU was used to view the models on graphics monitors.

10. Interactive computer programs were developed to : -

   a. Measure radiance data for mapping radiance over the region of contact.

   b. Generate 3-D maps of radiance from the data obtained by the data acquisition system and display the maps on graphics monitors.

c. Take samples of signals and apply Fourier Transformation to determine frequency distributions.

d. Generate 3-D information about rough surfaces from the Talysurf 4 profile meter and generate 3-D models on graphics monitors.

11. An Instruction Manual, describing all the computer programs and containing step by step procedures on how to use the systems developed in this study, was prepared.

8. Recommendations

The following are some suggestions on how to to improve the capabilities of the experimental systems discussed in the previous chapters.

8.1 Radiance Mapping

1. The manual scanning technique used in this study is definitely not the best way of scanning the region of contact to obtain data for the radiance maps. Stepper motors should be attached to the X-Y micrometer substage to automatically scan the region of interest. Automatic scanning will not only be more accurate, but will also enable the user to scan the region very quickly and hence get a more accurate picture of the radiance distribution at any time.

2. Emissivity maps should be generated and coupled with the radiance maps to generate accurate maps of the temperature distribution over the region of interest. The new system can be used to do this very quickly and precisely.

3. The number of scan lines and the number of nodes per scan line should be as high as possible for high resolution scanning.

4. The sliding system should be allowed to reach steady state before attempting to scan the region in order to avoid changes in radiance during scanning.

5. The data acquisition system should be used to study the effects of transfer films by measuring the radiance in one revolution, two revolutions and so on.

6. The color fringing technique demonstrated in Chapter 4 is a very useful tool and should be used to find temperatures above certain threshold values. It might even be possible to use this technique to determine the true area of contact.

8.2 Transient Measurements

1. Transient data should be recorded on magnetic tape and played back at a slower speed to the data acquisition system in order to compensate for the low frequency response of the digital system.

2. More extensive computer programs should be developed to perform statistical analyses on the digitized data.

3. The "AC" channel should be used to study thermal transients.

4. Extra memory should be added to the computer controlling the data acquisition in order to be able to take large samples from signals without having to down-load the data to disks between samples.

8.3 Surface Mapping

1. Since the surface mapping accuracy depends, to a large extent, on the traces of the stylus being parallel to each other, an automatic relocating system should be attached to the Talysurf 4 profile meter.

2. A better triggering system should be used to trigger the digitizer to ensure that each trace of the stylus starts from the same straight line.

3. A better X-Y precision table, with higher resolution, should be used to index the specimen along the Y axis after each trace of the stylus. If possible, this table should be attached to stepper motors for automatic indexing after each trace to improve accuracy.

4. Finite element analysis packages should be used to determine surface stresses and simulate surfaces in contact with each other.

References

1. **Furey, M. J.** "The Formation of Polymeric Films Directly on Rubbing Surfaces to Reduce Wear", Conf. on Physico-Chemical Mechanics of Friction and Wear, Kiev, U.S.S.R., 25-29 June 1973; *Wear*, Vol. 26, pp. 369-392, 1973.

2. **Furey, M. J.,** "The 'in situ' Formation of Polymeric Films Directly on Rubbing Surfaces", *Proceedings of International Conference on Polymers and Lubrication (Brest),* published by Centre National de la Recherche Scientifique, Paris, N0. 233, pp. 393-404, 1975.

3. "Surface Texture", ANSI B46.1 - 1978, ASME, New York, 1978.

4. **Furey, M. J.,** "Infrared Measurements of Surface Temperatures Produced in Tribological Processes", Third International Tribology Congress, Warsaw, Poland, Vol. 1, pp. 118-139, September 1981.

5. **Omori, D. I.,** "Infrared Measurements of Surface Temperatures Generated by Friction", Master of Science Thesis, Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va., August 1975.

6. **Richardson, M. H.,** "An Experimental Investigation of the Surface Temperature of Graphite in a Sliding System Using an Infrared Microscope", Master of Science Thesis, Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va, August 1976.

7. **Li, S. H.,** "Experimental Investigation of Surface Temperatures of Some Polymers in Unlubricated Sliding", Master of Science Thesis, Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va, August 1976.

8. **Rogers, C. A.,** "An Experimental Investigation of the Effect of Subdivision of Contact Area on Surface Temperatures Generated by Friction", Master of Science Thesis, Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va, December 1982.

9. **Moyer, S. C.,** "Infrared Radiometer Measurements of Surface Temperatures Generated by Friction of Sliding Iron on Sapphire", Master of Science Thesis, Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va, February 1983.

10. **Thomas, T. R.** (editor), *Rough Surfaces,* Longman Inc., New York, 1982.

11. **Guerrero, J. I.** and **Black, J. T.** "Stylus Tracer Resolution and Surface Damage as determined by Scanning Electron Microscopy", *Trans. ASME: J. Eng. Ind.*, **94B**, 1087-93, 1972.

12. **Edmonds, M. J., Jones, A. M., O'Callaghan, P. W.** and **Probert, S. D.**, "A Three-Dimensional Relocation Profilometer Stage", *Wear*, **43**, 329-40, 1977.

13. **McAdams, H. T., Picciano, I. A.** and **Reese, P. A.**, "A Computer Method for Hypsometric Analysis of Abrasive Surfaces", *Proc. 9th. Int. Machine Tool Des. and Res. Conf.*, Part2, 1149-72 (Pergamon, London), 1968.

14. **Wallach, J.**, "Surface Topography Description and Measurement" in Ling, F. F. (ed), *Surface Mechanics* (ASME, New York), 1-23, 1969.

15. **Grieve, D. J., Kaliszer, H.** and **Rowe, G. W.**, "A Normal Wear Process Examined by Measurements of Surface Topography", *Ann. CIRP*, *18*, 585-92, 1970.

16. **Deutch, S. J., Wu, S. M.** and **Straklowski, C. M.**, "A New Irregular Surface Measuring System", *Int. J. Mach. Tool Des. Res.*, 13, 29-42, 1973.

17. **Sayles, R. S.** and **Thomas, T. R.**, "Mapping a Small Area of a Surface", *J. Phys: Sci. Instrum.* **E9**, 855-61, 1976.

18. **Kelly, W. L., Burcher, E. E.** and **Skolant, M. W.**, "An Optical Profilometer for Spatial Characterization of Three Dimensional Surfaces", *NASA TP-1012*, 1977.

19. **Wyant, J. C., Koliopoulos, C. L., Bhushan, B.**, and **Basila, D.**, "Development of a Threee Dimensional Non-Contact Digital Optical Profiler", *Trans. ASME: J. Trib.*, paper no. 85-Trib-15, 1985.

20. **Kennedy, F. E.**, "Thermal and Thermomechanical Effects in Dry Sliding", *Wear* **100**, 453-476, 1984.

21. **Furey, M. J.**, "Surface Temperatures in Sliding Contact", *Trans. ASLE*, Vol. 7, pp. 133-146, 1964.

22. **Bowden, F. P.**, and **Thomas, P. H.**, "The Surface Temperature of Sliding Solids", *Proceedings of the Royal Society of London*, Ser. A, Vol. 223, pp. 29-40, 1954.

23. **Reichenbach, G. S.**, "Experimental Measurement of Metal Cutting Temperature Distributions", *Trans. ASME*, Vol. 80, pp. 525-46, 1958.

24. **Chao, B. T., Li, H. L.**, and **Trigger, K. J.**, "An Experimental Investigation of Temperature Distribution at Tool-Flank Surface", *Trans. ASME*, Ser. B, Vol. 83, pp. 496-504, 1961.

25. **Deyber, P.**, and **Godet, M.**, "Contact Temperatures in Mixed Friction", *Tribology*, August, pp. 150-4, 1971.

26. **Wiggins, J. M.**, "An Experimental Method for Measuring Surface Temperatures Generated by Friction", Master of Science Thesis, Mechanical Engineering, Virginia Polytechnic institute and State University, Blacksburg, Va, May 1975.

27. **Turchina, V., Sanborn, D. M.**, and **Winer, W. O.**, "Temperature Measurements in Sliding Elastohydrodynamic Point Contacts", *Trans. ASME: J. of Lubrication Technology*, pp. 236-243, April 1976.

28. **Wymer, D. G.,** and **Macpherson, P. B.,** "An Infra-red Technique for the Measurement of Gear Tooth Surface Temperature", paper, ASLE/ASME Lubrication Conf., Montreal, 8-10 Oct. 1974; *Trans. ASLE,* Vol. 18, N0. 4, pp. 229-238, 1975.

29. **Ausherman, V. K., Nagaraj, H. S., Sanborn, D. M.,** and **Winer, W. O.,** "Infrared Temperature Mapping in Elastohydrodynamic Lubrication", *Trans. ASME, J. of Lubrication Technology,* pp. 236-243, April 1976.

30. **Nagaraj, H. S., Sanborn, D. M.,** and **Winer, W. O.,** "Effects of Load, Speed, and Surface Roughness on Sliding EHD Contact Temperatures", *Trans. ASME, J. of Lubrication Technology,* pp. 254-263, April 1977.

31. *Talysurf 4, Operators Handbook,* Rank Taylor Hobson, England.

32. *Instruction Manual, Infrared Radiometric Microscope, Model RM-2A,* Barnes Engineering Company, Stamford, Conn.

33. *Data Translation Microcomputer Analog I/O Systems Catalog and Applications Guide,* Data Translation Ltd, Berks, U.K.

34. **Bowden, F. P.,** and **Tabor, D.,** *The Friction and Lubrication of Solids,* Oxford University Press, London, 1950.

35. *MOVIE.BYU, A General Purpose Computer Graphics System,* Brigham Young University, 1984.

36. **Hollowell, E. L.,** "Infrared Measurements of Steady-State Temperatures and Average Surface Temperature Distributions for Silver Sliding on Sapphire" Master of Science Thesis, Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Va., 1983.

Appendix

A. MOVIE.BYU

The MOVIE.BYU system, distributed by the Brigham Young University, requires a digital computer with a word length of at least 32 bits [35] . The elements of this system are FORTRAN programs for the display and manipulation of data representing mathematical, topological and architectural models, whose geometry may be described in terms of polygonal elements or contour line definitions. The programs in MOVIE provide the data in line drawing or continous tone image format, clip and cap 3-D systems to expose internal surfaces, allow modification of geometry, convert complex contour line definitions into polygonal elemental mosaics, allow viewing of multiple models simultaneously, etc. Interactive programs in this system also take care of the elimination of hidden lines and give the user full freedom to define the location of the light sources (with which the model is to be illuminated) and define the color of the model and produce a continuous tone realistic image of 3-D models.

The data to be displayed by MOVIE.BYU has to be in a format which can be read by the DISPLAY module of MOVIE.BYU. The format used in writing the geometry file is as follows:

If the variables are defined as

NP = Number of Parts

NJ = Number of nodes or joints

NPT = Number of elements or polygons

NCON = Number of entries in the connectivity array

NPL = The parts list

X = The coordinates of the nodes

137

IP = The connectivity of the elements or polygons

then the geometry file is written using the following FORTRAN statements:

WRITE (10,100) NP, NJ, NPT, NCON

WRITE (10,100) ((NPL(I,IJ), I = 1,2), IJ = 1,NP)

WRITE (10,200) ((X(I,IJ), I = 1,3), IJ = 1,NJ)

WRITE (10,100) (IP(I), I = 1,NCON)

100 FORMAT (16I5)

200 FORMAT (6E12.5)

As an example, the data used to generate the three-dimensional map of radiance shown in Fig. 32 is given below.

DATA STRUCTURE FOR DISPLAY WITH MOVIE.BYU

```
9  100  81  324

1   9  10  18  19  27  28  36  37  45  46  54  55  63  64  72

73  81

0.00000E+00 0.00000E+00 0.25561E-01 0.50000E-01 0.00000E+00 0.25988E-01

0.10000E+00 0.00000E+00 0.10256E+00 0.15000E+00 0.00000E+00 0.13450E+00

0.20000E+00 0.00000E+00 0.13927E+00 0.25000E+00 0.00000E+00 0.13693E+00

0.30000E+00 0.00000E+00 0.13404E+00 0.35000E+00 0.00000E+00 0.51452E-01

0.40000E+00 0.00000E+00 0.57089E-01 0.45000E+00 0.00000E+00 0.71065E-01

0.00000E+00 0.50000E-01 0.79283E-01 0.50000E-01 0.50000E-01 0.17158E+00

0.10000E+00 0.50000E-01 0.18457E+00 0.15000E+00 0.50000E-01 0.19097E+00

0.20000E+00 0.50000E-01 0.18635E+00 0.25000E+00 0.50000E-01 0.18463E+00

0.30000E+00 0.50000E-01 0.18046E+00 0.35000E+00 0.50000E-01 0.16158E+00

0.40000E+00 0.50000E-01 0.79167E-01 0.45000E+00 0.50000E-01 0.74036E-01

0.00000E+00 0.10000E+00 0.10251E+00 0.50000E-01 0.10000E+00 0.18286E+00

0.10000E+00 0.10000E+00 0.19126E+00 0.15000E+00 0.10000E+00 0.18555E+00

0.20000E+00 0.10000E+00 0.19278E+00 0.25000E+00 0.10000E+00 0.18136E+00

0.30000E+00 0.10000E+00 0.18220E+00 0.35000E+00 0.10000E+00 0.18366E+00

0.40000E+00 0.10000E+00 0.16742E+00 0.45000E+00 0.10000E+00 0.93863E-01

0.00000E+00 0.15000E+00 0.10192E+00 0.50000E-01 0.15000E+00 0.18225E+00

0.10000E+00 0.15000E+00 0.19378E+00 0.15000E+00 0.15000E+00 0.19079E+00

0.20000E+00 0.15000E+00 0.19030E+00 0.25000E+00 0.15000E+00 0.18801E+00

0.30000E+00 0.15000E+00 0.18854E+00 0.35000E+00 0.15000E+00 0.18766E+00

0.40000E+00 0.15000E+00 0.18439E+00 0.45000E+00 0.15000E+00 0.95925E-01

0.00000E+00 0.20000E+00 0.86884E-01 0.50000E-01 0.20000E+00 0.19187E+00

0.10000E+00 0.20000E+00 0.18228E+00 0.15000E+00 0.20000E+00 0.19071E+00

0.20000E+00 0.20000E+00 0.18923E+00 0.25000E+00 0.20000E+00 0.19135E+00

0.30000E+00 0.20000E+00 0.19430E+00 0.35000E+00 0.20000E+00 0.19888E+00

0.40000E+00 0.20000E+00 0.17095E+00 0.45000E+00 0.20000E+00 0.90898E-01

0.00000E+00 0.25000E+00 0.92423E-01 0.50000E-01 0.25000E+00 0.19291E+00

0.10000E+00 0.25000E+00 0.19236E+00 0.15000E+00 0.25000E+00 0.19339E+00
```

0.20000E+00 0.25000E+00 0.18825E+00 0.25000E+00 0.25000E+00 0.19301E+00

0.30000E+00 0.25000E+00 0.18713E+00 0.35000E+00 0.25000E+00 0.18971E+00

0.40000E+00 0.25000E+00 0.16824E+00 0.45000E+00 0.25000E+00 0.92088E-01

0.00000E+00 0.30000E+00 0.11101E+00 0.50000E-01 0.30000E+00 0.18567E+00

0.10000E+00 0.30000E+00 0.19425E+00 0.15000E+00 0.30000E+00 0.20075E+00

0.20000E+00 0.30000E+00 0.19329E+00 0.25000E+00 0.30000E+00 0.19240E+00

0.30000E+00 0.30000E+00 0.19581E+00 0.35000E+00 0.30000E+00 0.19442E+00

0.40000E+00 0.30000E+00 0.15398E+00 0.45000E+00 0.30000E+00 0.90770E-01

0.00000E+00 0.35000E+00 0.94406E-01 0.50000E-01 0.35000E+00 0.11816E+00

0.10000E+00 0.35000E+00 0.19718E+00 0.15000E+00 0.35000E+00 0.19622E+00

0.20000E+00 0.35000E+00 0.19822E+00 0.25000E+00 0.35000E+00 0.20068E+00

0.30000E+00 0.35000E+00 0.19552E+00 0.35000E+00 0.35000E+00 0.16592E+00

0.40000E+00 0.35000E+00 0.98359E-01 0.45000E+00 0.35000E+00 0.95077E-01

0.00000E+00 0.40000E+00 0.92795E-01 0.50000E-01 0.40000E+00 0.96126E-01

0.10000E+00 0.40000E+00 0.99158E-01 0.15000E+00 0.40000E+00 0.11468E+00

0.20000E+00 0.40000E+00 0.12811E+00 0.25000E+00 0.40000E+00 0.10276E+00

0.30000E+00 0.40000E+00 0.10220E+00 0.35000E+00 0.40000E+00 0.96486E-01

0.40000E+00 0.40000E+00 0.10047E+00 0.45000E+00 0.40000E+00 0.10222E+00

0.00000E+00 0.45000E+00 0.93021E-01 0.50000E-01 0.45000E+00 0.10928E+00

0.10000E+00 0.45000E+00 0.10174E+00 0.15000E+00 0.45000E+00 0.10489E+00

0.20000E+00 0.45000E+00 0.10009E+00 0.25000E+00 0.45000E+00 0.10030E+00

0.30000E+00 0.45000E+00 0.99189E-01 0.35000E+00 0.45000E+00 0.10459E+00

0.40000E+00 0.45000E+00 0.10515E+00 0.45000E+00 0.45000E+00 0.10100E+00

```
 1    2   12  -11    2    3   13  -12    3    4   14  -13    4    5   15  -14
 5    6   16  -15    6    7   17  -16    7    8   18  -17    8    9   19  -18
 9   10   20  -19   11   12   22  -21   12   13   23  -22   13   14   24  -23
14   15   25  -24   15   16   26  -25   16   17   27  -26   17   18   28  -27
18   19   29  -28   19   20   30  -29   21   22   32  -31   22   23   33  -32
23   24   34  -33   24   25   35  -34   25   26   36  -35   26   27   37  -36
27   28   38  -37   28   29   39  -38   29   30   40  -39   31   32   42  -41
32   33   43  -42   33   34   44  -43   34   35   45  -44   35   36   46  -45
36   37   47  -46   37   38   48  -47   38   39   49  -48   39   40   50  -49
```

```
41  42  52  -51   42  43  53  -52   43  44  54  -53   44  45  55  -54
45  46  56  -55   46  47  57  -56   47  48  58  -57   48  49  59  -58
49  50  60  -59   51  52  62  -61   52  53  63  -62   53  54  64  -63
54  55  65  -64   55  56  66  -65   56  57  67  -66   57  58  68  -67
58  59  69  -68   59  60  70  -69   61  62  72  -71   62  63  73  -72
63  64  74  -73   64  65  75  -74   65  66  76  -75   66  67  77  -76
67  68  78  -77   68  69  79  -78   69  70  80  -79   71  72  82  -81
72  73  83  -82   73  74  84  -83   74  75  85  -84   75  76  86  -85
76  77  87  -86   77  78  88  -87   78  79  89  -88   79  80  90  -89
81  82  92  -91   82  83  93  -92   83  84  94  -93   84  85  95  -94
85  86  96  -95   86  87  97  -96   87  88  98  -97   88  89  99  -98
89  90 100  -99
```

B. PROGRAM FUREY

Program FUREY is a program written in BASIC to facilitate scanning of a region of interest with the IR microscope. It is an interactive program and can be used only on an IBM PC with the DT 2805 I/O card. The program prompts the user to set the limits (X, Y coordinates) of the scan area. It then allows the user to set up the number of nodes in each direction. The scanning can then be started by manually moving the microscope using the X-Y table micrometers. The program samples the signal from the DC channel of the microscope and the two LVDT's and averages over 20 samples. It keeps the user informed about the position of the microscope by constantly displaying the node number. The user has to make sure that all the nodes have been traversed before allowing the program to save the two dimensional array of voltages (from the D C channel) on to a floppy disc from where it can be sent to the IBM 4341 host computei for further processing.

PROGRAM FUREY

```
1 CLEAR
4 DIM DATA.ARRAY!(125,100)
5 DIM TEMP.ARRAY!(7)
6 DIM SUM.DATA!(7)
10 DIM ANALOG.ARRAY%(7)
20 DIM GAIN%(7)
30 GAIN%(0) = 1
31 GAIN%(1) = 1
32 GAIN%(2) = 500
33 GAIN%(3) = 1
34 GAIN%(4) = 1
35 GAIN%(5) = 1
36 GAIN%(6) = 1
37 GAIN%(7) = 1
1060 CLS
1070 INPUT "SET DATE (Y-N)";G$
1080 IF G$ = "Y" THEN 1110
1090 IF G$ = "N" THEN 1190
1100 GOTO 1060
1110 INPUT "INPUT DATE (MM/DD/YY) ";D$
1120 INPUT "INPUT TIME (HH: MM: SS) ";T$
1130 TIME$ = T$
1140 DATE$ = D$
1190 ADC.VALUE = 3
1270 SET.ERROR.CONTROL.WORD = 75 :  GET.ERROR.CODE = 78
1370 ENABLE.SYSTEM.CLOCK = 177 :  DISABLE.SYSTEM.CLOCK = 180
1380 DEF SEG = &H0  ' get the PCLAB segment
1390 PCLSEG = PEEK ( &H4FE ) + 256*PEEK ( &H4FF )
1400 DEF SEG = PCLSEG ' REM address the PCLAB segment
1410 CLS
1420 INPUT"CALIBRATE 0R TEST (C OR T) ";G$
```

```
1430 IF G$ = "C" THEN GOTO 1460

1440 IF G$ = "T" THEN GOTO 1990

1450 GOTO 1410

1460 'REM CALIBRATE ROUTINE

1500 INPUT "WHAT CHANNEL (0-7)";G%

1510 IF G% > 7 OR G% < 0 THEN GOTO 1500

1520 CHANNEL% = G%

1540 GAIN% = 1

1550 ERROR.VALUE% = 0

1560 CALL SET.ERROR.CONTROL.WORD(ERROR.VALUE%)

1620 CALL GET.ERROR.CODE(ERROR.VALUE%)

1630 IF ERROR.VALUE% = 0 THEN 1660

1640 PRINT"AQUISITION ERROR ";ERROR.VALUE

1650 STOP

1660 CALL DISABLE.SYSTEM.CLOCK

1680 GOSUB 1900

1685 VOLTAGE! = (SINGLE%/409.6)/GAIN%

1690 CALL ENABLE.SYSTEM.CLOCK

1700 CALL GET.ERROR.CODE(ERROR.VALUE%)

1710 IF ERROR.VALUE% < >0 THEN PRINT "AQUISITION ERROR. ";ERROR.VALUE%

1780 LOCATE 10,30

1790 PRINT USING "CH ## = + ##.#######V. ";CHANNEL%,VOLTAGE!

1800 LOCATE 9,24

1810 PRINT "SYSTEM CHANNEL ";CHANNEL%;"   GAIN = ";GAIN%

1820 IF INKEY$ < >"" THEN GOTO 1410

1830 GOTO 1660

1840 CALL ADC.VALUE(CHANNEL%,GAIN%,SINGLE%)

1900 CALL ADC.VALUE(CHANNEL%,GAIN%,SINGLE%)

1910 IF GAIN% < > 500 AND SINGLE% = 4095 AND GAIN% < > 1 THEN GAIN% = GAIN%/10:
       GOTO 1900

1915 IF SINGLE% = 4095 AND GAIN% = 500 THEN GAIN% = 100: GOTO 1900

1930 IF GAIN% < > 100 AND SINGLE% < 409 AND GAIN% < > 500 THEN GAIN% = GAIN%*10:
       GOTO 1900

1940 IF SINGLE% < 819 AND GAIN% = 100 THEN GAIN% = 500 : GOTO 1900

1950 RETURN

1990 CLS

2000 'REM TEST ROUTINE
```

```
2001 CLS

2003 INPUT "INPUT NO. OF NODES PER TRACE";X.NUM%

2005 INPUT "INPUT NO. OF TRACES ";Y.NUM%

2007 INPUT "ARE NODES AND TRACES CORRECT ";G$

2009 IF G$ = "N" THEN 2001

2011 IF G$ = "Y" THEN 2020

2013 GOTO 2001

2020 FOR AVG = 1 TO 50

2021 FOR CHANNEL% = 0 TO 2

2070 CALL ADC.VALUE(CHANNEL%,GAIN%(CHANNEL%),ANALOG.ARRAY%(CHANNEL%))

2100 SUM.DATA!(CHANNEL%) = SUM.DATA!(CHANNEL%) + ANALOG.ARRAY%(CHANNEL%)

2105 NEXT CHANNEL%

2110 NEXT AVG

2115 FOR CHANNEL% = 0 TO 1

2120 TEMP.ARRAY!(CHANNEL%) = INT(SUM.DATA!(CHANNEL%)/50)

2130 NEXT CHANNEL%

2140 TEMP.ARRAY!(2) = ((SUM.DATA!(2)/50)/409.8)/GAIN%(2)

2150 FOR L = 0 TO 7: SUM.DATA!(L) = 0: NEXT L

2160 IF INKEY$ < > "" THEN GOSUB 4000

2200 'REM FILL DATA ARRAY

2205 IF STEPX! = 0 OR STEPY! = 0 THEN 2230

2210 X% = ABS(INT((TEMP.ARRAY!(0)-XS)/STEPX!))

2220 Y% = ABS(INT((TEMP.ARRAY!(1)-YS)/STEPY!))

2230 IF X% > 125 OR Y% > 100 THEN PRINT"***ARRAY ELEMENT T00 HIGH***": GOTO 3000

2235 IF ST = 0 THEN GOTO 3000

2240 DATA.ARRAY!(X%,Y%) = TEMP.ARRAY!(2)

3000 'REM PRINTOUT ON SCREEN

3001 LOCATE 4,28

3002 PRINT DATE$;" ";TIME$

3003 PRINT: PRINT

3005 PRINT USING "X  #####          Y #####          Z + ##.####### VOLTS";
     TEMP.ARRAY!(0)-XS,TEMP.ARRAY!(1)-YS,TEMP.ARRAY!(2)

3007 IF ST = 1 THEN PRINT USING "X  #####          Y #####          Z + ##.####### VOLTS";
     X%,Y%,TEMP.ARRAY!(2)

3009 PRINT: PRINT

3010 'REM FOR L = 3 TO 7: PRINT USING "CH # + ##.#### VOLTS";L,DATA.ARRAY!(L) : NEXT

3020 GOTO 2020
```

```
4000 'REM KEYBOARD INPUT ROUTINE

4005 GOSUB 4010: GOSUB 4090: GOSUB 4010: RETURN

4010 LOCATE 10,1

4020 PRINT " TYPE XS TO SET X START    ";XS

4030 PRINT " TYPE XE TO SET X END      ";XE

4040 PRINT " TYPE YS TO SET Y START    ";YS

4050 PRINT " TYPE YE TO SET Y END      ";YE

4060 PRINT " TYPE XD TO INPUT X DIST    ";XD

4070 PRINT " TYPE YD TO INPUT Y DIST    ";YD

4071 PRINT " TYPE ST TO FILL ARRAY      ";ST

4072 PRINT " TYPE SP TO SAVE ARRAY     "

4080 PRINT: RETURN

4090 INPUT G$

5000 IF G$ = "XS"THEN XS = TEMP.ARRAY!(0) : RETURN

5010 IF G$ = "XE"THEN XE = TEMP.ARRAY!(0) : STEPX! = ABS(XS-XE)/X.NUM%: RETURN

5020 IF G$ = "YS"THEN YS = TEMP.ARRAY!(1) : RETURN

5030 IF G$ = "YE"THEN YE = TEMP.ARRAY!(1): STEPY! = ABS(YS-YE)/Y.NUM%: RETURN

5040 IF G$ = "XD"THEN INPUT XD: RETURN

5050 IF G$ = "YD"THEN INPUT YD: RETURN

5060 IF G$ = "ST"THEN ST = 1 : RETURN

5070 IF G$ = "SP"THEN ST = 0: GOSUB 6000 : RETURN

5080 RETURN

6000 'REM SAVE ARRAY ROUTINE

6010 LOCATE 20,1

6020 INPUT "NAME OF FILE TO SAVE ON DISK ";FILE$

6030 OPEN FILE$ FOR OUTPUT AS #1

6034 PRINT #1,X.NUM%,Y.NUM%

6035 PRINT #1,XD/X.NUM%,YD/Y.NUM%

6040 FOR Y = 1 TO Y.NUM%

6050 FOR X = 1 TO X.NUM%

6060 PRINT #1,DATA.ARRAY!(X,Y)

6070 NEXT X

6080 NEXT Y

6090 CLOSE #1

6100 RETURN
```

C. PROGRAM SCOPE

Program SCOPE is a program written in FORTRAN to sample (and digitize), display and store data coming into the data acquisition system through any one (or more) of its eight analog input channels. Channels 0 through 5 are connected to the IR microscope and its accessories. Channel 6 is connected to the Talysurf 4 Profile-meter. The program is fully interactive and allows the user to first select the device he is using--the IR microscope or the Talysurf.

If the IR microscope is chosen, the program allows the user to select the channel (or channels) to be sampled, the sampling rate, the number of samples and the internal gain to be used. The data is then displayed on the screen in the form of a graph (voltage vs time) using Tektronix TCS. The user can then store the data on a disc if necessary.

If the Talysurf is chosen in the first stage, the user is prompted for the Talysurf magnification factor, stylus traverse speed, number of samples and the sampling rate. The digitized data is then converted to actual height (using a Talysurf calibration factor) and the data is displayed in the form of a graph of vertical displacement of the stylus (in microns) vs the stylus traverse length (in mm). The user can save the data on a disc.

PROGRAM SCOPE

```
$LARGE
     INTEGER*2 STATUS,STARTC,ENDCHA,GAIN,TIMING,SAMPLE
     INTEGER*2 XINIT,XTERM,XSB,XST,XSCD,ANALOG(2001),DATPTS
     INTEGER*2 XDLY,XSTB,XWD,XSC,XGC,XCEV,XREV,XGF,CHANLS
     INTEGER*2 XAV,XAOT,XSA,XAS,XBAD,XCAD,XTAD,XWAD,XSAD
     INTEGER*2 XDV,XDOT,XSD,XDS,XBDD,XCDD,XTDD,XWDD,XSDD
     INTEGER*2 XEFO,XEFI,XODV,XODOT,XIDV,XIDOT,XIXR,XIXW
     INTEGER*2 XSECW,XGDE,XRD,XFDL,XESC,XDSC,PLOTS,PLTPNT
     INTEGER*4 CLOCKD
     CHARACTER*9 FNAME
     CHARACTER*1 YES,YES1,YES2, YES3
     EXTERNAL XINIT,XTERM,XSAD,XSDD,XWD,XSC,XCEV,XESC,XDSC
     REAL X(2001),Y(2001)


     WRITE(*,*)
     WRITE(*,*)' ******************************************************'
     WRITE(*,*)
     WRITE(*,*)' THIS PROGRAM SAMPLES ANALOG INPUTS TO CHANNELS 1 '
     WRITE(*,*)' THROUGH 6 AND PLOTS THE RESULTS ON THE SCREEN.    '
     WRITE(*,*)
     WRITE(*,*)' CHANNELS 1 THROUGH 5 SAMPLE SIGNALS FROM THE     '
     WRITE(*,*)' INFRA - RED MICROSCOPE AND ITS ACCESSORIES.      '
     WRITE(*,*)
     WRITE(*,*)' CHANNEL NO. 6 SAMPLES SIGNALS FROM THE TALYSURF'
     WRITE(*,*)' PROFILE-METER.'
     WRITE(*,*)
```

```
      WRITE(*,*)' FOR THE INFRA-RED MICROSCOPE, ON ALL THE PLOTS, THE'
      WRITE(*,*)' X-AXIS REPRESENTS TIME AND THE Y-AXIS REPRESENTS'
      WRITE(*,*)' VOLTAGE.'
      WRITE(*,*)
      WRITE(*,*)' FOR THE TALYSURF, THE X-AXIS REPRESENTS THE DISTANCE'
      WRITE(*,*)' TRAVERSED BY THE TALYSURF ( IN MM.) AND THE Y-AXIS'
      WRITE(*,*)' REPRESENTS THE VERTICAL IRREGULARITIES (IN MICRONS)'
      WRITE(*,*)
      WRITE(*,*)' *****************************************************'
      WRITE(*,*)
10    STATUS = 0
      WRITE(*,*)
15    WRITE(*,*) ' I.R. MICROSCOPE OR TALYSURF ?(1 OR 2)'
      READ(*,*) HCNI
      INCH = INT(HCNI)
      IF (INCH.EQ.2) THEN
         STARTC = 6
         ENDCHA = 6
         GAIN = 1
23    WRITE(*,*)
      WRITE(*,*)
      WRITE(*,*) ' INPUT TALYSURF MAGNIFICATION FACTOR - AS SHOWN'
      WRITE(*,*) ' ON THE DIAL ON THE CONTROL UNIT'
      WRITE(*,*)
      READ(*,*) HMAG
      MAG = INT(HMAG)
      IF(MAG.NE.500.AND.MAG.NE.1000.AND.MAG.NE.2000.AND.MAG.NE.5000.
   &  AND.MAG.NE.10000.AND.MAG.NE.20000.AND.MAG.NE.50000.AND.MAG.NE.
   &  100000) THEN
         WRITE(*,*)
         WRITE(*,*)' ********************************************'
         WRITE(*,*)' THE MAGNIFICATION FACTOR IS INVALID !!!!!!'
```

```
      WRITE(*,*)' *******************************************'
      WRITE(*,*)
      GO TO 23
   ENDIF
   VFACT = 26800./MAG
   WRITE(*,*)
16 WRITE(*,*)' INPUT THE GEARBOX SPEED SETTING SHOWN ON THE'
   WRITE(*,*)' FRONT OF THE GEARBOX. INPUT : -'
   WRITE(*,*)'      1  FOR X100'
   WRITE(*,*)'      2  FOR X20'
   WRITE(*,*)'      3  FOR AV'
   WRITE(*,*)
   READ(*,*) GEAR
   IGEAR = INT(GEAR)
   IF(IGEAR.EQ.1) TFACT = 3.6/60.
   IF(IGEAR.EQ.2) TFACT = 18.3/60.
   IF(IGEAR.EQ.3) TFACT = 91.4/60.
   IF(IGEAR.NE.1.AND.IGEAR.NE.2.AND.IGEAR.NE.3) THEN
      WRITE(*,*)
      WRITE(*,*)' *******************************************'
      WRITE(*,*)' GEARBOX SETTING IS NOT VALID !!!!!!'
      WRITE(*,*)' *******************************************'
      WRITE(*,*)
      GO TO 16
   ENDIF
ELSE
   IF(INCH.NE.1) GO TO 15
   WRITE(*,*)
   WRITE(*,*)' *******************************************'
   WRITE(*,*)' CHANNEL 0 IS THE LVDT OUTPUT FOR X - POSITION'
   WRITE(*,*)' CHANNEL 1 IS THE LVDT OUTPUT FOR Y - POSITION'
   WRITE(*,*)' CHANNEL 2 IS THE DC OUTPUT FROM THE MICROSCOPE'
```

```
       WRITE(*,*) ' CHANNEL 3 IS THE AC OUTPUT FROM THE MICROSCOPE'
       WRITE(*,*) ' CHANNEL 4 IS THE OUTPUT FROM TORQUE TRANSDUCER'
       WRITE(*,*) ' CHANNEL 5 IS THE OUTPUT FROM THE SPEED COUNTER'
       WRITE(*,*) ' ************************************************'
       WRITE(*,*)
17     WRITE(*,*) ' START CHANNEL ? ( 0 - 5 )'
       READ (*,*) CSTART
       STARTC = INT(CSTART)
       IF(STARTC.LT.0.OR.STARTC.GT.5.) GO TO 17
18     WRITE(*,*) ' END CHANNEL ? ( 0 - 5 )'
       READ(*,*) AENDCH
       ENDCHA = INT(AENDCH)
       IF(ENDCHA.LT.0.OR.ENDCHA.GT.5) GO TO 18
       IF(ENDCHA.LT.STARTC) THEN
          IDUM = STARTC
          STARTC = ENDCHA
          ENDCHA = IDUM
       ENDIF
19     WRITE(*,*) ' GAIN ?  (1, 10, 100, 500) '
       READ(*,*) AGAIN
       GAIN = INT(AGAIN)
       IF(GAIN.NE.1.AND.GAIN.NE.10.AND.GAIN.NE.100.AND.GAIN.NE.500)
     &  GO TO 19
          TFACT = 1.0
          VFACT = 1.0
       ENDIF
20     WRITE(*,*)
       WRITE(*,*) ' ************************************************'
       WRITE(*,*) ' THE TOTAL SAMPLING TIME SHOULD BE LESS THAN 2.93 '
       WRITE(*,*) ' SECONDS. THE TOTAL SAMPLING TIME IS THE PRODUCT '
       WRITE(*,*) ' OF THE NUMBER OF CHANNELS, THE NUMBER OF DATA '
       WRITE(*,*) ' POINTS PER CHANNEL AND THE SAMPLING INTERVAL.'
```

151

```
        WRITE(*,*)
        WRITE(*,*) ' MOREOVER, THE TOTAL NO. OF DATA POINTS, i.e., THE'
        WRITE(*,*) ' PRODUCT OF THE NO. OF DATA POINTS AND THE NO. OF'
        WRITE(*,*) ' CHANNELS, SHOULD NOT EXCEED 2000.'
        WRITE(*,*) ' ************************************************'
35      WRITE(*,*)
        WRITE (*,21)
21      FORMAT(1X,'INPUT THE NUMBER OF DATA POINTS PER CHANNEL (4-8000)')
        READ(*,*)SDATPT
        DATPTS = INT(SDATPT)
        IF(DATPTS.GT.8000.OR.DATPTS.LT.4) THEN
           WRITE(*,*)
           WRITE(*,*)' ************************************************'
           WRITE(*,*)'    INVALID NUMBER OF DATA POINTS !!!!!!!'
           WRITE(*,*)' ************************************************'
           GO TO 35
        ENDIF
25      WRITE (*,30)
30      FORMAT(1X,'INPUT THE SAMPLING INTERVAL IN MILLI SECONDS ')
        WRITE(*,*)'   (.125 ms  to   165 ms)'
        READ(*,*)SAMP
        IF (SAMP.LT.0.125.OR.SAMP.GT.165.) THEN
           WRITE(*,*)
           WRITE(*,*) '*********************************'
           WRITE(*,*) ' SAMPLING INTERVAL IS INVALID !!!'
           WRITE(*,*) '*********************************'
           WRITE(*,*)
           GO TO 25
        ENDIF
        CLOCKD = INT(SAMP/.00250)
        TIMING = 0
        CHANLS = ENDCHA + 1 - STARTC
```

```
      SAMPLE = CHANLS*DATPTS
      SAMPT = SAMP*SAMPLE
      IF(SAMPLE.GT.8000) THEN
         WRITE(*,*)
         WRITE(*,*)' *********************************************'
         WRITE(*,*)' THE TOTAL NO. OF DATA POINTS EXCEEDS 8000 !!!'
         WRITE(*,*)' *********************************************'
         GO TO 20
      ENDIF
C   CHECKING FOR WAITING ERRORS
      ICH1 = SAMPLE*CLOCKD
      IF(ICH1.GT.1172000) THEN
50    WRITE(*,*)
      WRITE(*,*) ' *******************************************'
      WRITE(*,*) ' THE SAMPLING TIME IS TOO LONG !!!'
      WRITE(*,*)
      WRITE(*,60) SAMPT
60    FORMAT(1X,' YOUR SAMPLING TIME IS',F8.4,' SECS'/)
      WRITE(*,*) ' PLEASE CHANGE THE SAMPLING INTERVAL OR THE NO.'
      WRITE(*,*) ' OF DATA POINTS OR USE THE OTHER PROGRAM'
      WRITE(*,*)
      WRITE(*,*) ' QUIT OR CHANGE ? (Q OR C)'
      WRITE(*,*) ' *******************************************'
      WRITE(*,*)
       READ(*,'(A)') YES2
      IF (YES2.EQ.'Q') GO TO 20
      IF (YES2.NE.'C') GO TO 50
      GO TO 20
      ENDIF
40    WRITE(*,*) ' ****************************'
      WRITE(*,*) '    EXTERNAL TRIGGER ? (Y/N)'
      WRITE(*,*) ' ****************************'
```

```
        READ(*,'(A)') YES3

        IF ( YES3.EQ.'Y') TIMING = 2

        IF (YES3.EQ.'N')  TIMING = 0

        IF (YES3.NE.'N'.AND.YES3.NE.'Y') GO TO 40


        ANALOG(1) = SAMPLE
C   The following 'STATUS ='statements are functions that effect specified

C   operations on the interface card and if 'STATUS' is not zero an error

C   has occurred and the number delivered specifies the particular error

C   that can be used in error handling routines.
        STATUS = XDSC
C   Disable PC's time of day clock so it won't interrupt.
        STATUS = XRD
C   Reset 2801-A card.
        STATUS = XINIT
C   Initialize card.
        STATUS = XSCD(CLOCKD)
C   Set clock divider with number of ticks between samples.
        STATUS = XSA(TIMING, STARTC, ENDCHA, GAIN)
C   Set respective parameters on card.


80   STATUS = XDSC
C   Disable PC's time of day clock so it won't interrupt.
        STATUS = XBAD(SAMPLE, ANALOG(2))
C   Take specified no. of samples and fill array beginning

C   at specified element.
        STATUS = XWAD(ANALOG(SAMPLE))
C   Wait until specified element is filled before continuing.
        STATUS = XTERM
C   Terminate DMA operation with 2801-A card.
        STATUS = XESC()
C   Enable PC's time of day clock.
```

```fortran
      PLTPNT = 1
      TIMSUM = 0
      DO 95 PLOTS = 1,CHANLS
        DO 85 I = PLOTS,SAMPLE,CHANLS

          X(PLTPNT+1) = TIMSUM
          TIMSUM = TIMSUM+(FLOAT(CHANLS)*0.0000025*FLOAT(CLOCKD))*TFACT
          Y(PLTPNT+1)=((FLOAT(ANALOG(I+1))/409.6)/FLOAT(GAIN))*VFACT
85      PLTPNT = PLTPNT+1
        X(1) = FLOAT(DATPTS)
        Y(1) = FLOAT(DATPTS)


92      IF (INCH.EQ.2) THEN
          WRITE(*,*)
          WRITE(*,*)' DO YOU WANT TO SEE THE PLOT ? (Y/N)'
          WRITE(*,*)
        ELSE

          LOTS = PLOTS+STARTC -1
          WRITE(*,93) LOTS
93        FORMAT(//,1X,'DO YOU WANT TO SEE THE PLOT FOR CH.#',I2,' ?(Y/N)')
          WRITE(*,*)
          WRITE(*,*)
        ENDIF
        WRITE(*,*)' AFTER THE GRAPH IS PLOTTED, HIT ANY KEY TO CONTINUE'

        READ (*,'(A)') YES
        IF (YES.NE.'N') THEN
          IF(YES.NE.'Y') GO TO 92

          CALL INITT(1)
          CALL BINITT
```

155

```fortran
         CALL CHECK(X,Y)
         CALL DSPLAY(X,Y)
         CALL TINPUT (IOP)
         WRITE(*,120)
120      FORMAT(24(/))
      ENDIF
94    IF (INCH.EQ.2) THEN
         WRITE(*,*)
         WRITE(*,*)' DO YOU WANT TO SAVE THE ARRAY ? (Y/N)'
         WRITE(*,*)
      ELSE
         WRITE(*,97) LOTS
97    FORMAT(/,1X,'DO YOU WANT TO SAVE THE ARRAY FOR CH.#',I2,' ?(Y/N)')
         WRITE(*,*)
      ENDIF
      READ (*,'(A)') YES1
      IF (YES1.EQ.'Y') THEN

         WRITE(*,*)
         WRITE(*,*)
         WRITE (*,*) 'GIVE THE NAME OF THE FILE(<9 CHARACTERS)'
         WRITE(*,*)
         WRITE(*,*)
         READ (*,'(A)') FNAME
         OPEN(9,FILE=FNAME,STATUS='NEW',FORM='FORMATTED')
         WRITE (9,*) DATPTS
         DO 100 I=1,DATPTS
            WRITE (9,*) X(I)
            WRITE (9,*) Y(I)
100      CONTINUE
         CLOSE(9)
      ELSE
```

```fortran
          IF(YES1.NE.'N') GO TO 94
       ENDIF
       PLTPNT = 1
95     TIMSUM = 0
       WRITE(*,*)
       WRITE(*,*)
107    WRITE (*,*) ' DO AGAIN, CHANGE PARAMETERS, QUIT ?  (1, 2 OR 3)'
       WRITE(*,*)
       WRITE(*,*)
       READ(*,*) RQEST
       IF(RQEST.EQ.1) GO TO 80
       IF(RQEST.EQ.2) GO TO 10
       IF(RQEST.EQ.3) GO TO 110
       GO TO 107
110    CALL FINITT(0,0)
       END
```

D..PROGRAM 3DMAP

Program 3DMAP is a program written in EXEC2 language for the VM/CMS operating system. This is an extensive, interactive program for the following purposes:

1. Generate and display radiance maps in 3-D using MOVIE.BYU.

2. Generate and display surface maps in 3-D using MOVIE.BYU.

3. Display maps previously generated.

This program is capable of reading files created by Program FUREY and generating files containing 3-D information for the 3-D maps of radiance. These files can be directly read by the "Display" module of MOVIE.BYU and displayed on graphics terminals.

Program 3DMAP is also capable of reading a series of files created by parallel traverses of the stylus of the Talysurf 4 (using Program SCOPE) and generating files containing 3-D information for the 3-D maps of the rough surfaces. These files are then used by MOVIE.BYU for graphics display.

Progam 3DMAP also allows the user to display geometry files created previously. It allows the user to display the geometry either automatically (by going through MOVIE commands itself) or manually (by allowing the user to step through the MOVIE commands). This program calls a few FORTRAN programs to generate the geometry files.

PROGRAM 3DMAP

```
&TRACE ON
CLEAR
&BEGTYPE 26
```

```
**************************************************************
******************* DR. MICHAEL J. FUREY  ********************
**************************************************************
**                                              **
**        3-D RADIANCE AND SURFACE MAPPING SYSTEM        **
**                             **
**************************************************************
******************* JAYARAM  SANKAR   ***********************
**************************************************************
```

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
BLACKSBURG, VIRGINIA 24061
FEBRUARY 04, 1986

```
WAIT........

CP SLEEP 6 SEC
CLEAR
&LOOP 1 5
&TYPE
&BEGTYPE 14
*****************************************************************
*    THIS SYSTEM GENERATES 3-D MAPS OF :                  *
*                                    *
*            1. RADIANCE DATA FROM THE INFRA RED MICROSCOPE   *
*            2. SURFACES FROM PROFILE-METER DATA         *
*            3. PREDEFINED 3-D GEOMETRY             *
*                                    *
*    THE GRAPHICAL CAPABILITIES OF THIS SYSTEM REQUIRE A GRAPHICS  *
*    TERMINAL CAPABLE OF SUPPORTING MOVIE.BYU.             *
*                                    *
*****************************************************************
```

        PRESS < RETURN > TO CONTINUE

```
CP SLEEP
-10
CLEAR
&BEGTYPE 9
```

        DO YOU WANT TO MAP RADIANCE DATA OR SURFACE PROFILE ?

            TYPE S FOR SURFACE
            TYPE R FOR RADIANCE
            TYPE D IF YOU JUST WANT TO DISPLAY EXISTING GEOMETRY

TYPE Q TO QUIT

&READ VARS &GEN
&IF .&GEN EQ .Q &GOTO -500
&IF .&GEN EQ .S &GOTO -100
&IF .&GEN EQ .D &GOTO -200
&IF .&GEN NE .R &GOTO -10
-50
CLEAR
&BEGTYPE 8

        FOR GENERATING THE FILE CONTAINING THE INFORMATION
        REGARDING THE 3-D GEOMETRY OF THE RADIANCE MAP, YOU
        SHOULD HAVE A FILE GENERATED BY THE PROGRAM ·
        "FUREY" ON THE DATA ACQUISITION SYSTEM.

        DO YOU HAVE THE APPROPRIATE FILE ? (Y/N)

&READ VARS &YES
&IF .&YES NE .N &SKIP 13
-70
CLEAR
&BEGTYPE 6
        SORRY!! YOU CANNOT GENERATE A RADIANCE MAP USING THIS
        PROGRAM IF YOU DO NOT HAVE THE DATA IN THE PROPER
        FORMAT.

        DO YOU WANT OT GENERATE A SURFACE MAP ? (Y/N)

&READ VARS &YES1
&IF .&YES1 EQ .Y &GOTO -100
&IF .&YES1 NE .N &GOTO -70
&GOTO -400
&IF .&YES NE .Y &GOTO -50
-75
CLEAR
&BEGTYPE 4

DO YOU WANT TO SEE A LIST OF FILES GENERATED BY THE PROGRAM "FUREY"?(Y/N)

&READ VARS &YES7
&IF .&YES7 EQ .N &SKIP 1
LISTFILE * TEST *
&IF .&YES7 NE .Y &GOTO -75

&BEGTYPE 6

        GIVE THE NAME OF THE FILE YOU WANT TO USE
         (FILENAME & FILETYPE)

        TYPE Q TO QUIT

&READ VARS &FIL1 &FIL2
&IF .&FIL1 EQ .Q &GOTO -400
FILEDEF 7 DISK &FIL1 &FIL2 A
CLEAR
&BEGTYPE 7

        GIVE THE NAME OF THE FILE IN WHICH YOU WANT
        TO STORE THE 3-D GEOMETRY INFORMATION
         (ONLY FILENAME)

```
&READ VARS &FIL3
FILEDEF 8 DISK FILE &FIL3 A
CLEAR
&BEGTYPE 8


                    GIVE THE NAME OF THE FILE IN WHICH YOU WANT
                    TO STORE THE INFORMATION FOR THE CONTOUR LINES
                         ( ONLY FILENAME)


                    TYPE Q TO QUIT
&READ VARS &FIL4
&IF .&FIL4 EQ .Q &GOTO -400
FILEDEF 9 DISK FILE &FIL4 A
CLEAR
LOADMOD TEMPMAP
START
&GOTO -150
-100
CLEAR
&BEGTYPE 17



              FOR GENERATING THE FILE CONTAINING THE INFORMATION
              REGARDING THE 3-D GEOMETRY OF THE SURFACE, YOU
              SHOULD HAVE FILES CONTAINING THE DATA FROM THE
              TALYSURF, AS GENERATED BY THE PROGRAM "SCOPE"
              ON THE DATA ACQUISITION SYSTEM. EACH TALYSURF
              TRACE SHOULD BE IN A SEPARATE FILE .




              YOU CAN HAVE UPTO 27 FILES FOR EACH MAP.

              DO YOU HAVE THE NECESSARY FILES ? (Y/N)

&READ VARS &YES3
&IF .&YES3 NE .N &SKIP 10
CLEAR
&BEGTYPE 7


              SORRY!! YOU CANNOT GENERATE A SURFACE MAP USING THIS
              PROGRAM IF YOU DO NOT HAVE THE DATA IN THE PROPER
              FORMAT.

&GOTO -450
&IF .&YES3 NE .Y &GOTO -100
CLEAR
&BEGTYPE 7


              GIVE THE NAME OF THE FILE IN WHICH YOU WANT
              TO STORE THE 3-D GEOMETRY INFORMATION
                   ( ONLY FILENAME)
```

161

```
&READ VARS &FIL3
FILEDEF 8 DISK FILE &FIL3 A
CLEAR
&BEGTYPE 11




            GIVE THE NAME OF THE FILE IN WHICH YOU WANT
            TO STORE THE INFORMATION FOR THE CONTOUR LINES
                    ( ONLY FILENAME)



 .      &READ VARS &FIL4
        FILEDEF 9 DISK FILE &FIL4 A
        -125
        CLEAR                .
        &TYPE      HOW MANY FILES DO YOU WANT TO USE ? (< 27)
        &TYPE
        &TYPE
        &READ VARS &A
        &IF .&A GT 27 &GOTO -125
        &B = 0
        &LOOP 11 &A
        &B = &B + 1
        CLEAR
        &TYPE
        &TYPE
        &TYPE GIVE THE FILENAME AND FILETYPE FOR FILE NUMBER &B
        &TYPE
        &TYPE           TYPE Q TO QUIT
        &READ VARS &SURF &DATA
        &IF .&SURF EQ .Q &GOTO -400
        &COUNT = &B + 20
        FILEDEF &COUNT DISK &SURF &DATA A
        FILEDEF 7 DISK OUT OUT A
        CLEAR
        LOAD APPENDG(CLEAR
        START
        CLEAR
        LOADMOD TEMPMAP
        START
        -150
        CLEAR
        &BEGTYPE 6




            DO YOU WANT TO SEE THE GEOMETRY YOU JUST CREATED ? (Y/N)

        &READ VARS &YES4
        &IF .&YES4 EQ .N &GOTO -400
        &IF .&YES4 NE .Y &GOTO -150
        -200
        CLEAR
        &BEGTYPE 6
```

```
          ARE YOU ON A GRAPHICS TERMINAL WHICH SUPPORTS MOVIE.BYU ? (Y/N)
&READ VARS &YES5
&IF .&YES5 NE .N &SKIP 7
CLEAR
&BEGTYPE 4


          SORRY! DISPLAY IS NOT POSSIBLE WITHOUT A PROPER TERMINAL !
&GOTO -450
&IF .&YES5 NE .Y &GOTO -200
&IF .&GEN NE .D &SKIP 15
CLEAR
&LOOP 1 5
&TYPE
&BEGTYPE 2
          GIVE THE NAME OF THE FILE WHICH CONTAINS THE
               GEOMETRY INFORMATION
&READ VARS &FIL3
&BEGTYPE 6



          GIVE THE NAME OF THE FILE WHICH CONTAINS THE
               CONTOUR INFORMATION
&READ VARS &FIL4
-250
CLEAR
&LOOP 1 5
&BEGTYPE 4
               AUTOMATIC OR MANUAL ? (A/M)

               TYPE Q TO QUIT

&READ VARS &YES6
&IF .&YES6 EQ .Q &GOTO -400
&IF .&YES6 NE .M &SKIP 3
FILEDEF 5 TERMINAL
FILEDEF 6 TERMINAL
&GOTO -300
&IF .&YES6 NE .A &GOTO -250
&STACK &FIL3
EXECIO 1 DISKW FILE COMM A 1 (FINIS
FILEDEF 5 DISK FILE COMM A
FILEDEF 6 DUMMY
-300
EXEC DISPLAYT
FILEDEF 5 TERMINAL
FILEDEF 6 TERMINAL
-400
CLEAR
-450
&BEGTYPE 6



          WOULD YOU LIKE TO CREATE OR DISPLAY ANOTHER GEOMETRY ? (Y/N)
&READ VARS &YES6
&IF .&YES6 EQ .Y &GOTO -10
&IF .&YES6 NE .N &GOTO -400
-500
```

```
CLEAR
&BEGTYPE 23




***********************************************************************
********************   DR. MICHAEL J. FUREY   *************************
***********************************************************************
**                                        **
**              HAVE A GOOD DAY !               **
**                                  **
***********************************************************************
********************   JAYARAM  SANKAR   ***********************
***********************************************************************
        VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
             MECHANICAL ENGINEERING DEPARTMENT
                BLACKSBURG,  VIRGINIA 24061
                   FEBRUARY 04, 1986



CP SLEEP 4 SEC
CLEAR

&EXIT
```