DEVELOPMENT OF LIMB VOLUME MEASURING SYSTEM

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The development of ultrasonic plethysmography from a technical concept to a flight certified unit capable of measurements in space (zero G) environment has been the result of long term collaborative between the principal investigator and his associates with the National Aeronautic and Space Administration (NASA) personnel. This project was interdisciplinary in nature and required contributions from a variety of individuals.

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ABSTRACT

The mechanisms underlying the reductions in orthostatic tolerance associated with weightlessness are not well established. Contradictory results from measurements of leg volume changes suggest that altered veno-motor tone and reduced blood flow may not be the only contributors to orthostatic intolerance. It is felt that a more accurate limb volume system which is insensitive to environmental factors will aid in better quantification of the hemodynamics of the leg. Of the various limb volume techniques presently available, the ultrasonic limb volume system has proven to be the best choice. The system as described herein is free from environmental effects, safe, simple to operate and causes negligible radio frequency interference problems. The segmental ultrasonic plethysmograph is expected to provide a better measurement of limb volume change since it is based on cross sectional area measurements. Limb volume change is computed from the two cross-sectional areas measured at different sites (fixed length apart) using an equivalent right circular cylinder geometry. A space qualified version of our device has been built by Denver Research Institute and is expected to be used in a future space shuttle mission.
I. INTRODUCTION

The study and evaluation of cardiovascular deconditioning during space flight impose unique requirements on the limb volume measuring system (LVMS). The LVMS must operate, in both earth and zero gravity environments, be simple to calibrate and respond to both small and large changes in limb volume and be largely insensitive to humidity, ambient temperature and pressure variations.

The objective of this project was to develop a new technique for real time measurement of lower limb volume changes in space. The technique developed in this study, the ultrasonic plethysmograph, is based on transit time measurement of an acoustic pulse propagating through tissue. A microprocessor based ultrasonic lower limb volume measuring system was developed as a prototype system for use in space flight applications. It is based on the assumption that the cross section of the lower limb can be approximated by a circle. On this basis two independent chord length measurements using ultrasonic through transmission technique are made at a given site on the lower limb. This data is used by the microprocessor to compute the area of a circle passing through the measured chord lengths.

This report details the development of the ultrasonic limb volume measuring system into a flight certified unit which is expected to be used in a future space flight mission.

II. Background

A. Plethysmography

Plethysmography is the recording of variations in the volume of a liquid or undissolved gas in biological tissue. Studies of
peripheral circulation have been carried out through a variety of methods which record/measure the volume of blood content in a limb (plethysmography).

The principle of plethysmography was first introduced by Glissonio (1677) who used water displacement for limb volume measurement (1). Variations of this method, some using air as the displaced fluid, are still used for the measurement of arterial flow into segments or distal portions of limbs. Another frequently used plethysmograph is the Whitney strain gage, introduced in 1953 (2). The Whitney, or mercury-in-rubber, strain gage is attached around the limb segment in question and any relative change in the electrical resistance of the strain gage is used as a measure of a change in circumference of that limb segment. The accuracy of this method of plethysmography was compared to that of water displacement plethysmography by Paulev, et al. (1). They found that "the accuracy of the water and strain-gage plethysmograph is identical, and the two instruments closely follow random variations in blood flow." However, they further state that "The results of the strain-gage plethysmograph are dependent on the actual location of the strain gage."

Other methods of plethysmography include impedance and capacitance plethysmography. Impedance plethysmography (rheography) makes use of the fact that the electrical impedance of a limb segment varies with its blood content. Capacitance plethysmography involves the use of the skin as one plate of a capacitor. An electrode attached to a band around the limb segment completes the capacitor. Assuming a purely radial expansion with increased limb volume, the change in capacitance between the skin and the electrode is proportional to the change in volume of the limb segment. These and
other currently used methods of plethysmography are discussed more thoroughly by Sigdell (3). A comparative analysis of their feasibility for space flight applications may be found in an earlier report from this laboratory (4).

B. Relationship of Orthostatic Tolerance to Limb Volume Changes

Reductions in orthostatic tolerance due to exposure to zero G environment were first reported during the late flights of Mercury when tilt table tests conducted post-flight revealed moderate orthostatic hypotension. These findings were also observed during the Gemini program (flight duration 3-14 days). However, responses to the 70 degree upright tilt usually returned to normal within fifty hours after splash down (5,6).

During the Apollo program (7), a new test procedure, lower body negative pressure (LBNP) was used to study orthostatic tolerance. LBNP has several advantages over tilt table testing, some of which are:

1. No movement of subject is required which leads to simplified instrumentation and stable physiological signals.

2. Ease of application of controlled stress (magnitude and duration) to the cardiovascular system.


LBNP studies were performed for most Apollo crews, and the response of cardiovascular system during weightlessness was inferred from pre-flight and post-flight data. The results demonstrated reduced orthostatic tolerance, which returned to normal within 48 hours. Supine measurements of maximal calf circumference were also performed, before and after flight, of 24 crewmen. During post-flight evaluation 67% of crewmembers showed significantly reduced calf circumference, and this was not totally regained approximately 120
hours after splash down (7,8).

During the Skylab Program, the LBNP experiments were performed during missions 2, 3 and 4 to determine the extent and time course of changes in orthostatic tolerance during weightlessness (9). An additional objective was to determine whether the inflight data can be used for prediction of post-flight orthostatic tolerance status. LBNP produced exaggerated blood pressure and heart rate responses during the first inflight test of Skylab 2 crew, but did not show a trend towards the pre-flight levels during the 28-day flight. It was observed that cardiovascular responses to LBNP tended to become more stable after six to eight weeks of flights, but no trend toward pre-flight levels could be seen. Johnson et al (9) suggest that total blood volume may already have been reduced by the time first inflight LBNP tests were performed, and that a significant fraction of fluids previously located in the legs was now accommodated by veins and interstitial tissues of the upper part of the body. Thornton and Hoffler (10) conducted studies of lower limb during the Skylab 4 mission to test the hypotheses that changes in hemodynamics of legs with increased blood pooling and reduction in cardiac output is the most probable cause of orthostatic intolerance following spaceflight. In spite of the individual variability, the data showed increased blood flow above pre-flight and post-flight levels. Vascular compliance changes were high for both the scientist pilot and pilot whereas for the commander there was little change, and post-flight data showed return to pre-flight values of compliance. Based on scant data from three crew members, the authors were unable to further prove their hypothesis. However, their findings support the need for
careful assessment of pressure flow relationship in the lower limb.

Measurement techniques used in these redistribution studies include estimates of leg volume using multiple tape measurements of limb circumference, standard and infrared photography, and center of mass measurement (7,8). During the Skylab 3 and 4 missions, limb volume measurements were made using a space qualified version of the capacitance limb volume system developed by Barnett et al (11). This system represented the best available at that time for measurement of limb volume, although it is affected by environmental factors, such as humidity and temperature variations. In addition, all of these techniques suffer from the difficulty that considerable crew effort is required to obtain data, or that the transducers are bulky and cannot be used during launch or normal activities. For this reason, no experiments could be performed during the first hours and days of zero-gravity.

C. Requirements for a Space Flight Qualified Plethysmograph

Based on previous research (4) it is felt that an ideal space flight plethysmograph should have the following characteristics:

1. Operation in both zero and earth gravity environment.
2. Insensitive to humidity.
3. Insensitive to ambient temperature and pressure variation.
4. Compatible in size and operation with LBNP test procedures.
5. Simplicity of operation and calibration.
6. Reliable and safe.
7. Nonconfining and non-restrictive of limb dimensional changes.
8. Insensitive to limb movement.
9. Must respond to both small and large changes in limb volume.
ULTRASONIC PLETHYSMOGRAPHY

Ultrasonic plethysmography is based on measurement of transit time required for an ultrasonic pulse to propagate from one given point to another. If the velocity of the propagating sound wave in the medium under study is known, then measurement of transit time leads to computation of the pulse traversed distance, \( d \):

\[
d = c \cdot t
\]

where \( c \) = velocity of sound in the medium (m/sec)

\( t \) = measured transit time (sec)

Velocity of propagation of acoustic waves have been measured and reported in selected animal tissues using pulse echo techniques. Goss et al (12) provide a comprehensive listing of published results on acoustic properties of mammalian tissues. For a given frequency and temperature, the velocity of propagation appears to be constant and the range of variation is quite small for soft tissues. The average velocity of sound in soft tissues (excluding fat tissue) is \( 1560 \pm 20 \) m/sec at \( 2.25 \) MHz (Bhagat et al (12), Kadaba (13)). The temperature dependence of sound velocity in the range of \( 20-40 \) degrees C shows a variation of less than \( 2 \) m/sec/degree C. Since the temperature within the living tissue is maintained constant by the body within very narrow limits, temperature related errors can be safely ignored.

The use of ultrasonic transit time measurements for biological studies was first reported by Rushmer et al (14) who monitored left ventricular dimensions in open chested laboratory animals. Stegall and colleagues (15,16) have reported the instrumentation and results associated with implementation of the transit time principles.

Stegall et al (17) in an abstract dealing with noninvasive diagnosis of peripheral vascular disease suggested the use of an
ultrasonic dimension gauge to measure changes in lower limb dimensions. However, we have been unable to find any details on its actual implementation. We were the first to demonstrate the feasibility of ultrasonic dimension gauge for noninvasive monitoring of lower limb dimensions (18). In this approach, two ultrasonic transducers (resonant at 2.25 MHz) are placed across the limb segment under study. One of the transducers is shock excited which causes it to vibrate at its natural frequency. This ultrasonic vibration is transmitted through the limb and is converted into an electrical signal by the receiving transducer. The time period between initiation of the shock pulse and its reception by the receiving transducer can, therefore, be accurately measured. With the knowledge of acoustic velocity in the lower limb, the segment dimension is easily obtained.

The most critical choice for ultrasonic plethysmography of lower limb segment is that of transducers' natural frequency. Ultrasonic waves are attenuated when propagating through biologic media. The amplitude of the propagating wave decreases by an exponential factor given by

\[ P_0(f) = e^{-2a(f)x} P_i(f) \]  \hspace{1cm} (2)

where \( P_0(f) \) is the amplitude at a distance \( x \) in the medium
\( a(f) \) is the attenuation coefficient of the medium (dB/cm)
\( P_i(f) \) is the input wave
and \( f \) is the frequency of the wave.

Measurements in our laboratory (19) indicate that the attenuation coefficient \( a(f) \) is approximately linearly related to ultrasonic frequency \( a(f) = af^b; \ b = 1.06 \) for excised muscle tissue in
experimental animals. In light of this it is imperative that the ultrasonic frequency be kept as low as possible.

As the ultrasonic frequency is lowered two constraints come into play. In most transit time measurement systems arrival of the ultrasonic pulse is threshold detected with an amplitude comparator. Thus the maximum error due to threshold adjustment can be $\lambda/4$, where $\lambda$ is the wavelength of ultrasound. Assuming an average velocity of 1,560 m/sec, and calf length of 15 cms, in the range of 2-3 MHz the maximum threshold error is approximately 0.2 mm.

Further as ultrasonic frequency is lowered the thickness of crystal increases. Higher shock voltages are required at lower frequencies to set the transducer into vibration, due to its increased inertia. While this is not critical in most applications since the excitation voltages are usually in the range of 100-200v and are of short duration (4 ns), the authors feel that from a safety viewpoint every attempt should be made to keep these voltages lower.

We, therefore, chose frequency range of 2-3 MHz for the plethysmographic applications.

**SINGLE CHORD ULTRASONIC PLETHYSMOGRAPH**

The single chord ultrasonic plethysmograph is schematically shown in Figure 1. The major components of this instrument are a pulse generator (Pinger) and receiver amplifier, a voltage comparator, a sync pulse generator and an elapsed time counter. The system is housed in a single unit, with the exception of the transmitting and receiving piezo-electric crystals. The crystals are cut from 1" square L2T-5 stock, resonant at 2 MHz, with approximately 3 mm diameter, and then wires are attached. The crystals are dipped in
REPETITION RATE
1 kHz

1 MHz OSC.

1000

ONE-SHOT.

I m.S.

10 μ SEC.

THRESHOLD

AVAILANCE PULSE GEN.

PUL short

ULTRASONIC SIGNAL

RECEIVER AMP

IMPEDANCE MATCH

VIDEO MONITOR

PIEZOELECTRIC TRANSDUCERS

COMPARATOR

(10 μ SEC. DELAY)

COUNT ENABLE

COUNT LATCH

12 BIT LATCH

12 BIT D/A CONVERTER

ANALOG

OUTPUT

DIGITAL OUTPUT

DIMENSION OFFSET

OFFSET LOAD

ONE-SHOT

12 STAGE COUNTER

12 BIT OUTPUT

THUMB-WHEEL SWITCHES

32 MHz OSC.

FIGURE 1

SCHEMATIC OF SINGLE TRANSMITTER ULVS

9
clear epoxy to maintain the integrity of the transducer material over a period of time. The crystals are positioned on a limb such that the ultrasonic pulse will travel from the transmit crystal to the receiver crystal. The wave propagation time between crystals is measured by counting the number of cycles generated by a time base oscillator. Output from the system is available as a 12-bit binary number or an analog signal derived from the binary number through a digital-to-analog converter (DAC).

The measurement cycle begins on the leading edge of a 40 ns wide negative-going pulse. This pulse is generated by a monostable multivibrator (IC6, Fig. 2) triggered by a crystal controlled oscillator and frequency divider at a repetition rate of 1 KHz. This pulse induces a 150-V signal across a piezoelectric crystal. Due to this shock excitation, the crystal vibrates at its natural frequency, 2 MHz, resulting in the transmission of an ultrasonic signal across the limb.

The pinger circuit (Figure 3) works as follows:

When the trigger level is high (+15V) the base to emitter junction in transistor Q₁, is non conductive, therefore, no current flows through it. This also implies that transistor Q₂ will also be off and no signal is available across the transformer to the ultrasonic crystal. However, when the trigger level is lowered to zero, Q₁ and therefore Q₂ are turned on. With Q₂ in the operating mode a 200V signal is induced through the 1:1 transformer to excite the transmitting transducer. The transformer is included in the pinger circuit to provide isolation of 200V source from the test media (usually human subjects). The 200V signal is derived from a commercially available module (ERG) which is a dc to dc inverter with
FIGURE 3

AVALANCHE PULSE GENERATOR (PINGER) CIRCUIT
Simultaneous to the triggering of the transmitter circuit, the elapsed time counter (IC's 10-13, Fig. 2) is cleared and the time base signal (32 MHz) is gated to the input (IC 10) of the counter. The count accumulates until the voltage comparator senses a signal from the ultrasonic receiver which exceeds the operator controlled threshold voltage.

The input signal to the ultrasonic receiver (Fig. 4) comes from a piezoelectric receiving crystal attached to the limb. The receiving crystal is connected to the primary winding of $T_2$ which is balanced by a 1 kohm potentiometer and a 220 µf capacitor to provide common mode rejection. Transformer $T_2$ also provides electrical isolation for the subject. The signal induced in the secondary of $T_2$ is then amplified by a factor of 1,000 with two cascaded RF amplifier (LM371). The resulting signal serves as input to the voltage comparator (LM306).

Once the comparator senses the received signal, the time base signal being input to the counter is halted. After a short delay, allowing for propagation delays in the counter, the final count is latched in a separate register. The digital-to-analog converter changes the 12-bit register output to a proportional voltage which is recorded by an analog recorder. The register output can also be input into a computer system for data storage and analysis. A portion of the output can be suppressed by dialing in a number on a set of thumbwheel switches. The negative value of this number is loaded into the counter at the beginning of each measurement cycle thereby subtracting the number from every measurement. This feature allows
ULTRASONIC RECEIVER-AMPLIFIER AND COMPARATOR

FIGURE 4

+12V

+12V

-15V

COMPARE
DISABLE

VIDEO
MONITOR

TRIGGER
THRESHOLD

Q3

Q4

Q5

5.6K

6.2

IN914

5.6K

3.9K

2.7K

300

0.01

220P T2

300

1.5K

3.3K

2.2K

LM306

LM371

LM371

680P

680P

INPUT
BALANCE

TRANSDUCER
INPUT
the operator to record only the variations from a baseline reading. The distance resolution of this system using a 32 MHz clock is given by \( \text{resolution} = \frac{\text{sound velocity}}{\text{clock frequency}} = 0.049 \text{ mm} \). This system has been described in literature (18).

Extensive experimentation was carried out using human subjects to investigate the reliability, accuracy and repeatability of the developed instrument. Experimental protocols are defined below:

a) Static tests

With the subject in a supine position on a tilt-table, the instrument was tested by inducing a small precise changes in leg diameter. A 2 MHz transducer was mounted on each tip of a 5 in. micrometer. With the micrometer rigidly clamped, the leg of the subject was positioned so the micrometer spanned the major chord length from near the crest of the tibia to the back of the gastroenemius. The micrometer head was advanced until the crystals made firm contact with the skin. The chord length was then varied by advancing the micrometer head in steps of \(0.025 \text{ in} \) (0.635 mm). The change in the chord length as measured by the ultrasonic system is shown in Figure 5. As can be seen from the figure the system response to discrete step changes from 11.74 cm diameter to 11.30 cm diameter is repeatable as well as accurate.

b) Dynamic tests

A comparative study using Whitney Strain Gauge, (WSG), "Mercury in rubber" plethysmograph, was carried out to establish the dynamic performance of the system. If the limb segment involved in the plethysmographic measurement is assumed to be circular and the path between the ultrasonic transducers is assumed to be its diameter, then the cross-section area or volume per unit length of the limb
FIGURE 5

STATIC MEASUREMENTS OF DIMENSIONAL CHANGES ON THE LOWER LEG USING ULVS
segment is directly proportional to the measured distance. Any change in volume is, therefore, reflected in a change in travel time of the ultrasonic pulse. The Whitney Strain Gauge measures changes in circumference of the limb. Based on this hypothesis the plethysmographic measurements by the WSG and the ultrasonic plethysmograph, placed over the same limb segment, should be linearly related.

A typical cross-section of the lower leg in a healthy adult, at the level of limb segment normally involved plethysmography studies, is shown in Fig. 6 with approximate transducer locations. As can be seen from the figure, the ultrasonic distance measured is more like a chord of the limb segment. However, the ultrasonic output and the Whitney Strain Gauge output should still be related by a constant.

In this experiment, venous occlusion was used to produce a discrete change in limb volume. A pressure cuff was applied to the proximal portion of the limb and the pressure in the cuff was increased above the venous pressure but below the diastolic arterial pressure (usually between 20-60 mm Hg). Because the arterial inflow of blood was not stopped, there would be a net increase in the volume of the limb below the cuff due to a pooling of blood in the segment. The rate of volume change with respect to time immediately after occlusion can be used to determine the rate of blood flow in the arteries. The volume will stabilize when the pressure in the veins reaches the cuff pressure. This is known as the compliance level and, along with the initial rate of volume change, is one of the important parameters in venous occlusion plethysmography. A more thorough discussion of the mechanisms of venous occlusion plethysmography is
(→) Approximate position of transducers

1. Tibia
2. M. flexor digitorum longus
3. V. saphena magna et n. saphenus
4. V. et a. tibialis posterior
5. N. tibialis
6. M. soleus
7. Tendo m. plantaris
8. M. gastrocnemius
9. N. cutaneus surae medialis
10. V. saphena parva
11. N. cutaneus surae lateralis
12. M. gastrocnemius
13. A. et v. peronaeus
14. Fibula
15. N peronaeus superficialis
16. Mm. peronaei longus et brevis
17. N. peronaeus profundus
   a. et v. tibialis anterior
18. Mm. extensores longi digitorum et hallucis
19. Membrana interossea cruris
20. M. tibialis anterior

FIGURE 6
Cross sectional view of lower limb at the level of plethysmograph application.
given by Sigdell (3).

The apparatus used for this study includes two ultrasonic transducers, a Whitney strain gauge, a system for obtaining venous occlusion of the lower limbs, and the single chord ultrasonic plethysmograph.

The venous occlusion system, shown in Figure 7, consists of a twelve gallon fixed displacement air compressor (a), a pressure attenuator (b) for limiting the pressure in a small pressurized tank (c), two normally closed solenoids (d), and standard thigh cuffs equipped with sphygmomanometers. Upon activation of the first solenoid in the system, the pressure in the thigh cuffs is increased in approximately a stepwise matter. The amount of pressure in each cuff is determined from the sphygmomanometers. Once the first solenoid is deactivated the pressure in the thigh cuffs remains constant until the second, release, solenoid is activated.

With the subject relaxed in a supine position, the ultrasonic transducers are positioned on the lower leg at the level shown in Figure 6, using the oscilloscope to determine the position corresponding to maximum signal. Once the optimum position is determined, the transducers are taped in place using the smallest piece of tape necessary for secure placement. The Whitney strain gauge is then placed over the same limb segment as shown in Fig. 8 schematically and a photograph is shown in Fig. 9. The leg is, then, elevated slightly to eliminate pressure on the calf muscle and to prevent drag on the strain gauge. The thigh cuffs are applied to both legs above the knee.

After a stable base line is obtained on both channels of the chart recorder, the initial readings of the ultrasonic digital display
a) 12 gallon fixed displacement air compressor
d) Normally closed ASCO solenoids electrically controlled by a two-way switch
b) Pressure attenuator
e) Standard thigh cuffs with sphygmomanometers
c) Small pressure tank

FIGURE 7

Schema of system for inducing venous occlusion in lower limbs.
a. Ultrasonic transducer taped in place
b. Whitney strain gage
c. Ultrasound connection wires— to oscilloscope, digital display, and chart recorder
d. Strain gage connection wires—to gage display and chart recorder

FIGURE 8
Relative placement of ultrasonic transducer and Whitney strain gage
FIGURE 9

PHOTOGRAPH SHOWING ACTUAL LOCATIONS OF ULTRASONIC TRANSDUCERS AND WHITNEY STRAIN GAUGE
and the strain gauge display are recorded. The thigh cuff pressure is then increased to 20 mm Hg and held constant until the chart recorder graph reaches a maximum (compliance level). Readings are again recorded for the strain gauge display and the ultrasonic digital display. The pressure is then released and the system allowed to stabilize. This procedure is repeated for pressures of 30, 40 and 50 mm Hg. In this project at least three complete sets of data (i.e. pressures of 20-50 mm Hg) were taken during each session. Data sets were taken for each leg under the conditions of bilateral and unilateral venous occlusion. However, the equipment did not permit collection of data from both legs simultaneously.

To facilitate the interpretation of chart recorder data in terms of physical parameters (i.e. change in length per unit time and percent change in length at compliance), it was necessary to perform calibration experiments for the Whitney strain gauge and the ultrasonic system. The calibration of the ultrasonic system has been described under static test.

The calibration procedure for the Whitney strain gauge was as follows: One end of the strain gauge was fixed and the other end attached to a vernier device. The system was adjusted to an initial position with the strain gauge straight but not extended. The strain on the strain gauge was then incremented in 1 mm steps to a total of 10 mm strain. The gauge reading was recorded at each increment to check the linearity of the readings. The strain gauge was then returned to its initial length in steps of 1 mm and the readings were again recorded. Figure 10 shows the static data for Whitney strain gauge.

A typical venous occlusion record is shown in Figure 11. Cuff
L incremented by 1 mm
Gain = 5 volts full scale

FIGURE 10
Calibration curve for Whitney strain gage
as recorded on chart recorder
FIGURE 11: DYNAMIC COMPARISON OF WHITNEY GAUGE AND ULVS MEASUREMENTS
occluding pressure of 50 mm Hg was applied to the subject identified by pressure on arrow on the graph. The occlusion was maintained for a time period of approximately 2 minutes when the ultrasonic plethysmograph output reached steady state. The occluding pressure was released then and the record indicates a rapid emptying of the pooled blood followed by a slower decline to baseline values. Calculations of maximal blood flow and compliance levels can be made and the procedure is illustrated in Figure 12.

Figure 13 shows initial slope of the ultrasonic plethysmograph plotted against initial slope obtained using the Whitney strain gauge. The equation of the line shown in this figure, as determined by the least square error method, is

\[ W = 2.235 u + 0.176 \]

The above equation was derived using data from 30 independent experiment runs. The correlation is quite good \((r=0.9077)\).

Figure 14 shows the average initial slope as a function of cuff pressure. As can be seen, the initial slope remains approximately constant for pressures of 20-40 mm Hg and drops off slightly when the cuff pressure is 50 mm Hg. One possible explanation is that 50 mm Hg occluding pressure may have caused occlusion of some arterial vessels and thus decreasing the inflow rate.

The compliance level showed a direct dependence on the applied cuff pressure. Both the ultrasonic plethysmograph and the Whitney strain gauge outputs leveled off around the same time frame. Figure 15 shows a plot of compliance time versus cuff pressure for two subjects. As expected time to reach final compliance level increased with the applied occluding pressures.
Arterial inflow = \frac{dv}{dt}

Compliance level = V_c

Figure 12 Computation of arterial flow and compliance level
\[ \Delta w = 2.235 \Delta u + 0.76 \]

FIGURE 13: Correlation between initial slope of ultrasonic and Whitney strain gage plethysmographs
FIGURE 14: Average initial slopes (ultrasound and strain gage) as a function of cuff pressure
FIGURE 15: Compliance time versus cuff pressure
TWO CHORD ULTRASONIC LIMB VOLUME SYSTEM

A single dimension measurement is not a true indicator of the volume change in the lower limb. It was felt that a more accurate measure of limb volume could be obtained through computation of a cross-sectional area from two independent chord length measurements. The independent chord lengths are measured ultrasonically through placement of ultrasonic transducers around the circumference of the limb. We exploit the well known concept from analytic geometry that three points in a plane can define a unique circle. Our implementation of this concept uses three transducers, located on the limb. Two of these transducers, kept a fixed distance apart and located on one side of the limb act as transmitters of ultrasonic energy. This energy is received by the third transducer which is located on the opposite side of the limb. Thus, two independent transit time measurements can be made at any given site on the limb. With the knowledge of ultrasonic propagation velocity, the chord lengths can be computed as described earlier in this report. It may be noted that this computation also provides a sort of "averaging" of the ultrasonic chord length measurements, whenever the tissue expansion is approximately isotropic even when the cross-section is noncircular. A microprocessor was incorporated into the system to provide real time computations of limb cross-section, as well as to control the entire measurement process. Further the use of a microprocessor makes it easy to change the computational and control routines thus facilitating subsequent refinements of the design.

Theoretical details:

The following mathematical scheme defines the procedure for computation of the cross-sectional area from chord length
measurements:
Consider Figure 16 where OA and OB are the chord length obtained from
the measured transit times using transmitters (located at A and B
respectively) and receiver transducer (located at O). The distance,
AB, between the transmitters is fixed and known = D \text{ cm} and

\[
\begin{align*}
OA &= t_{OA} \\
OB &= t_{OB}
\end{align*}
\]

Where \( t_{OA} \) and \( t_{OB} \) are times required for the ultrasonic pulse to be
received at O from the sites at A and B respectively.

Without any loss of generality we can assumed that OA defines the
x axis. Hence the x-coordinate of the center

\[
x_c = \frac{D}{2}
\]

(1)
The equation of the circle passing through O, A and B with center \((x_c, y_c)\) is given by:

\[
(x-x_c)^2 + (y-y_c)^2 = r^2
\]

(2)

Where 'r' is the radius of the circle.

At the point O(0, 0) the equation is

\[
(D/2)^2 + y_c^2 = r^2
\]

(3)

and at the point B \((x_2, y_2)\)

\[
(x_2-D/2)^2 + (y_2-y_c)^2 = r^2
\]

(4)

also

\[
D_3^2 = D_1^2 + D_2^2 - 2D_1D_2 \cos \theta
\]

(5)

solving equations 3, 4 and 5 for radius, \( r \), we obtain
FIGURE 16. Computation of cross-sectional area from two chord length measurements
\[ r^2 = x_c^2 + y_c^2 \]
\[ = \frac{D_1^2 D_2^2 D_3^2}{(D_1 + D_2 - D_3)(D_1 + D_2 + D_3)(D_1 + D_3 - D_2)(D_1 - D_2 - D_3)} \] (6)

Area of the circle passing through O, A and B is

\[ \pi r^2 \]

which can be easily computed with knowledge or radius, r.

Equation 6 was simulated on both a minicomputer and a microcomputer for computational accuracy using several chord length sizes. All calculations were carried out in floating point arithmetic. The program, written in assembly language using Intel 8080 microprocessor chip, took approximately 1.5 k memory space. The accuracy of microprocessor computations was compared with that obtained using a DEC PDP-11/10 minicomputer and the results were in excellent agreement with each other. The truncation error in area computations using \( D_1 = 6.54 \) cm; \( D_2 = 7.55 \) cm and \( D_3 = 1.85 \) cm was \( 5 \times 10^{-3} \%), \) an insignificant error. It should be noted that these computations are affected by accuracy in measurement of \( D_3 \) (which must be accurate to within 0.1 mm). A large \( D_3 \) provides very accurate computations but leads to practical problems in implementation of the concept since the bony tissue, tibia, must not be in path of ultrasonic transmission. In addition, operational difficulties with actual placement of transducers dictate the transmitters be mounted on the same assembly. We have determined that \( D_3 \) of the order of 2.5 cm provides a good compromise between computational accuracy requirements and operational ease. (21).
Details of the developed instrument:

A. **Hardware Description:**

The developed instrument (Fig. 17) is housed in a Tektronix TM 515 Mainframe. An SC 502 oscilloscope is included to monitor the quality of received signals. The instrument is modular with transmitters, receiver, and processor circuits housed in separate compartments. Transmitter and receiver circuits are identical to those described earlier for the single chord ultrasonic plethysmograph. Two separate transmitter (pinger) circuits are provided. Either of these pinger circuits can be selected by the processor, providing independent measurement of the two chord lengths. The piezoelectric transducer elements, which are mounted in specially-molded housings for attachment to the limb, are connected to the instrument by unshielded twisted pair cables.

**Processor and Memory:** A block diagram of the implemented circuits is shown on Figure 18. The system uses one Intel 8080 CPU with a clock generator (8224), which provides 18 MHz for the counter and the timing frequency of 2 MHz for the CPU. 256 byte random access memory (RAM) is used for storage of generated data and a 2kb read only memory (ROM) is available for storage of software codes and constants needed for computation of cross-sectional area. The data lines from CPU are latched through a data bus and control status bus driver in order to increase the drive capacity of the CPU. Two peripheral interface adapters (PIA) are used: one connects the data bus to LED display through four BCD to seven segment decoder/drivers while the other interfaces the counter to the CPU. Due to the available number of lines on the PIA chosen the output display is limited to less than 200 cm$^2$ (The 5th digit of the display is wired so that it will show...
FIGURE 17: Two transmitter ULVS
Figure 18. Block Diagram of ULV Electronics.
blank or "1" only). This restricts the maximum calf diameter to less than 16.5 cms. For the normal adult population this is not a serious limitation. The power for all the units is derived from the TM 515 power module with suitable regulators to obtain ± 12 V and ± 5 V.

Transmitter Select and Counter Control Logic: The 12-bit binary counter is interfaced with the CPU through PIA as shown. The 18-MHz clock frequency provides 56 ns resolution for time measurements. Following transmitter activation, the comparator output is inhibited for 10 μs to allow electrical interference from the transmitting pulse to decay. This block also contains transmitter select and level conversion circuitry necessary for producing a pulse from one of the two transmitters. The command pulse which fires the selected transmitter also starts the counter. The counter continues to count until it is stopped by a level change signal from comparator.

A three-position switch (mode switch) is used to select the modes of operation of the unit. Each of the first two positions causes one of the two transmitters to be "pinged" at a 2-KHz rate. The receiver amplifier and comparator outputs are displayed on the oscilloscope so that the quality of the received signal can be assessed. The pinger and receiver amplifier circuits are shown in Figures 3 and 4 of this report.

Transducer Assembly: The two transmitting crystals are mounted in a plexiglass assembly which is curved to fit the shape of the leg. The distance between the two crystals is set at approximately 2.5 cm. This spacing was selected as a compromise between computational accuracy and ease of fabrication. Crystals are cut from sheets of lead zirconium titanate transducer material (LTZ-2), with a resonant
frequency of approximately 2 MHz. The transmitting crystals are relatively large (5 mm diameter), in order to ensure an adequate signal level at the receiver. The receiving crystal is smaller (2 mm). Use of a small crystal makes the receiver less directional, but does not seriously reduce signal amplitude. All the crystals are fitted with lenses which produce a wider beam width than would be provided by the crystal alone.

B. Software Description:

The instructions necessary to operate the instrument are contained within the 2K ROM. This ROM contains, in addition to operating instructions, subroutines for floating point arithmetic and for conversion of floating point numbers into a code suitable for output to the LED display. Computations are carried to five significant figures.

The operating routines are designed to make use of the instrument as simple as possible. When the three-position selector switch is in the OPERATE position, pushing RESET causes the instrument to output a series of voltage levels on the analog output. These voltage levels produce a calibration record for the strip chart recorder.

The instrument next measures two chords and computes a baseline value for the cross-sectional area. Chords are then measured at a rate of about 10/s. Simultaneous with the analog output, the computed cross-sectional area is sent to the display. The analog output is scaled so that full scale deflection of the recorder represents +6% to -2% volume change.

Two digital filters are used to improve the appearance of the analog output. A slew rate filter serves to limit the effect of
occasional false comparator triggers. This filter functions by limiting to three steps the maximum change allowed in the 8-bit D/A converter in one sampling interval. Thus, very large and sudden deviations are not passed to the output.

A one pole low-pass filter is used to reduce the effect of digitization and other noise on the analog output. This filter requires storage of one previous value of the output and one multiplication. Implementation, therefore, requires only a minimum of processor time and memory. In the current version of the software, the time constant of the filter is set at about 3 s.

Additional details regarding actual hardware and software implementation can be found in Appendix C.

C. Operation of the Instrument:

To use the instrument, ultrasonic transducers must be properly attached to the subject's leg. Transducers are mounted using exercise EKG adhesive collars (Beckman). The transducers are attached first at midcalf level in such a way as to avoid passing the ultrasonic pulse through the bones of the leg. This is conveniently accomplished by placing the received transducer just to the inside of the tibia. The transmitter assembly is then moved around the rear half of the calf until adequate signals are obtained. By use of the three-position selector switch, the signal from either of the two transmitting crystals can be displayed on the oscilloscope screen. The position of the receiving transducer is adjusted until an acceptable signal is obtained from both transmitters. When such a position is found, the selector switch is set to the OPERATE position. Pushing RESET causes the instrument to produce a series of calibration levels before beginning to measure and output fractional changes in leg volume. The
analog output of the ULVS should be connected to a strip-chart recorder with ±2.5 V full scale sensitivity.

Comparison of ULVS with other plethysmographic techniques:

The developed two transmitter ULVS was used in a study by NASA (22) to compare the sensitivity and accuracy of our methodology. A population of thirty subjects (50% male) was used. These subjects were non-paid volunteers (age 18-45), in good health with no evidence of varicosity. Tests were carried out in an environmental chamber with controlled temperature and humidity. The Whitney Strain Gauge was used as a standard and compared against our ULVS and an impedance plethysmograph. Figure 19 shows the system electrode placements and the results of a 50 mm Hg venous occlusion are shown in Figures 20. The correlation coefficient between the WSG and ULVS for the computed limb volume was 0.996. The maximum volume indicated by the ULVS was consistently higher than the corresponding WGS output. The impedance plethysmograph gave similar results when compared against WSG (22).
CURRENT-SUPPLYING ELECTRODES

SENSING ELECTRODES

THIGH PRESSURE CUFF

ULTRASOUND ELECTRODE

SITE OF ONE ULTRASOUND ELECTRODE IN WHITNEY/ULTRASOUND TESTING, SECOND ELECTRODE APPROXIMATELY 135° AROUND BELLY OF GASTROCNEMIUS MUSCLE.

= SITE OF IMPEDANCE ELECTRODES IN WHITNEY/IMPEDANCE TESTING.

FIGURE 19. SYSTEM ELECTRODE PLACEMENT
FIGURE 20. COMPARISON OF ULVS AND WHITNEY DIMENSION MEASUREMENT UNDER VENOUS OCCLUSION
AMBULATORY ULTRASONIC PLETHYSMOGRAPHY:

The following technical requirements were developed in consultation with responsible NASA personnel for fabrication of an ambulatory ultrasonic limb plethysmograph, ULP.

Overall System Requirement:

The contractor (equipment fabricator) shall be required to produce a flight qualified, portable four transmitter ultrasonic plethysmograph capable of measuring two limb cross sections simultaneously based on the designed two transmitter ultrasonic plethysmograph. The following additional constraints were also incorporated:

1. The ULP shall be capable of being attached to the crewmembers during launch and re-entry.

2. The ULP shall be capable of interfacing with the Experiment Data Interface (EDI) as specified.

3. The built-in Data Recording System (DRS) shall be capable of intermittantly recording ULP data during launch and re-entry.

4. The ULP shall operate on battery power.

5. The ULP shall be capable of operation from a DC power supply through an umbilical from the EDI.

6. The ULP shall be capable of operating continuously for 30 hours. One sample per second should be taken during this period.

7. The built-in DRS shall be capable of:

   (a) Recording chord length sets determined at rates between one and ten times per second.

   (b) Storing 1 to 4 megabits of data.

   (c) Recording quiet period indications.

   (d) Recording the 12 bit chord lengths generated by the ULP and the time associated with that data.

   (e) Remotely turning on, taking data and then turning off.
General Design Requirements:

The total package for STS ULP shall be a portable, battery powered unit with dimensions not to exceed 2.5" x 5" x 8" including the batteries. The ULP shall not exceed .8 Kgs weight. The outputs of the ULP shall interface with the EDI. An on-off switch with an indicator light shall be provided on the ULP.

Data outputs from the ULP include:

1. An output of chord length $D_1$ digitally coded. This output interfaces the EDI.

2. An output of chord length $D_2$ digitally coded. Interfaces EDI and DRS.

3. Outputs of chord lengths $D_1'$ and $D_2'$ representing second leg cross-section, each digitally coded. These outputs interface the EDI and DRS.

4. Several outputs which can be accessed allowing internal parameters to be monitored. These outputs are defined under hardware test points (additional requirements).

5. Timing output and quiet period indications. These interface the EDI.

The ULP is made up of several subsystems which each perform a specified function. The subsystems should follow the specifications of the two transmitter ULVS developed at University of Kentucky and use minimization techniques to reduce size. Exceptions to these specifications are noted in the following:

**Transducers**

The ULP shall incorporate six piezoelectric crystals which are used as ultrasonic transducers. These transducers will be placed across the lower limb of the subject in two sets of three. Two of the transducers in each set act as transmitters of ultrasonic pulses, and the third transducer of each set acts as a receiver. The resonant frequency of these transducers is about 2.25 MHz.
Pinger Circuit

The pinger circuit shall provide the capability to excite a preselected ultrasonic transmitter by inducing a 100 to 150 volt, 10 nanosecond positive pulse. Modifications shall be made to eliminate the need for a -15V power supply.

Controller Logic, Transmitter Select and Counter

The function of this subsystem is to control the flow of information throughout the system, to select a transmitter for chord length measurement and to provide a count proportional to the measured ultrasonic transit time. The basic counter frequency shall be 18 MHz for this subsystem. This system supplies the following functions:

1. Provides interfacing to processor.
2. Provides mode selection for transducer placement and ultrasonic signal visualization.
3. Starts and stops counter.
4. Inhibits receiver section for an adjustable period of time to reduce the possibility of false output.
5. Selects the transmitter that is to be activated.

Receiver Circuit and Comparator

The ultrasonic signal receiving amplifier shall have a gain of 60 dB (min) and have standard wide band video capabilities. The receiver shall be transformer coupled to the ultrasonic transducer to provide high common mode rejection. The signal to noise ratio (SNR) shall be at least 40 dB. The comparator shall be a level detector at $0.2 \pm 0.02$ V measured at the output of the receiver amplifier.

Processor and Memory

This subsystem provides a timing signal for operation of the ULP. The timing signal shall be derived from a 18.0 MHz clock which will also be used for the binary count. A microprocessor, equivalent to
the 8080, shall be used for all command and store operations. The computational constants and instructions should be stored on permanent memory. Data output shall be interfaced through the processor. This subsystem shall drive a display on the ULP. The processor shall also provide command operations to the DRS.

Additional Requirements:

Hardware Tests Points

A connector shall be accessible which allows the following phenomena to be monitored:

1. The analog signals of the transmitters.
2. The analog signals of the receivers.
3. The comparator output. (digital)
4. The calculated cross sectional area measurement.
5. The 18 MHz time base. (digital)
6. The Pinger voltage

Self-Test Button

This button should be available to activate programmed inputs into the processor for calibration and check-out.

Quiet Period Indicator

An indicator for quiescent periods and sleep period shall be incorporated into the design of the ULP. These indications are to be imposed on the data.

Physical Configuration

Throughout the design phase of the program, weight, volume and power consumption minimization shall be a prime consideration within the measurement, operational and environmental constraints imposed herein. The ULP electronics shall be configured in one package. An
on-off switch shall be supplied on the electronics package. This package shall be two output connectors. One output shall provide chord transit time data, timing outputs and quiet period indications. The other output connector shall be able to provide all internal information which is required herein. The package shall be easily attached to the crewmembers and be comfortable to wear.

Range

The ULP shall have the capability to demonstrate the following characteristics:

1. Provide reliable measurements on calf lengths up to 18 cms corresponding to limb circumference of approximately 57 cms.

2. Duration of a single cross sectional area measurement shall not exceed 50 mseconds.

3. The chord length measurement must be accurate to within ± 0.6 mm for a nominal chord length of 14 cms.

4. The digital counter shall be 12 bits.

Calibration

The capability to inject appropriate calibration and test signals into the STS ultrasonic plethysmograph just prior to initiation of a data gathering sequence should be provided. This will be initiated whenever the self-test button is depressed.

Display

A four digit display shall be provided on the ULP which displays instantaneously to the crewmembers the measured chord length of the limb cross-sectional area. The display shall be visible to the crewmembers at all time during operation.

Battery Monitor

The ULP system shall have a battery check system and a warning if the battery power is low.
Optimum Signal Locator

A method of detecting transducer placement for the optimum signal without using an oscilloscope shall be incorporated. This method can be an envelope detector. A blinking display can be used to show that the optimum signal is not being received.

Ground Support Equipment

The Ground Support Equipment (GSE) to be developed in support of this program shall include as a minimum the following:

1. Playback equipment to allow playback of tapes recorded by the DRS.

2. ULP Data Interface Simulator (DIS). The DIS will be designed to emulate the ULP Data Interface with the EDI in amplitude, impedance, and format content to allow development and verification of hardware and software in, and down-stream of, the EDI. DIS electrical connectors need not be flight type.

The tape playback equipment should be supplied at the time of delivery of the first ULP prototype system containing a built-in DRS.

Delivery of the DIS will be required at least two months prior to delivery of the ULP prototype in order to allow timely development of the EDI and associated hardware and software.

Denver Research Institute, DRI, fabricated a prototype test unit for our evaluations in accordance with a test plan developed by us. Results of these tests are detailed in the "Appendix B".

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The use of an ultrasonic micrometer in limb plethysmography has been described in this report (page 6). This technique, ultrasonic pulses are created through shock excitation of a piezo-electric transducer. After transit through the coupling medium, a second piezo-electric transducer converts the acoustic energy into an electrical signal. If the sound velocity in the medium is known and constant, the propagation time between the two crystals is an accurate measure of the separation distance. Arrival of the pulse at the receiver crystal is detected by the triggering of a comparator set just above the noise level of the receiver amplifier. In the usual situation the received signal level is very much larger than the noise level; changes in comparator firing time can then be confidently interpreted as changes in tissue dimension. If pulse amplitude is not much higher than the comparator level, however, small changes in signal amplitude or pulse shape will cause changes in comparator firing time. This will be falsely interpreted as a change in tissue dimension. Although these considerations are important in all applications of sonomicrometry, they are especially critical in plethysmographic applications, where very small dimension changes are measured.

To routinely obtain good signals, it is essential that well-designed transducers be available. The most critical requirement is that the beam pattern of the transducers must be sufficiently wide. Adequate signal amplitude can then be obtained with minimum care in placement of the transducers. In addition, small rotations of the transducers, which may occur during a limb expansion, will not affect
pulse shape substantially.

Two basic types of transducers for ultrasonic dimension measurements have been described in the literature, chiefly for use in cardiac dimension measurements. One type is constructed from a disk cut from flat stock piezo-electric ceramic. Size of the disk may vary from 2 mm to 5 mm in diameter, with the smaller diameters having the wider beamwidth. A convex plastic lens is added to diverge the beam [14,15,16]. This type of transducer has the advantage that it is inexpensive and simple to construct. The beamwidth of the transducers, however, is quite narrow, even with the addition of a diverging lens. Thus, careful orientation of the transducers is required. Small rotations of the transducers may produce relatively large changes in pulse amplitude and shape even after careful placement of the transducers on the tissue.

A second type of transducer has been more recently described [27]. This transducer uses a hemispherically shaped piezo-electric element which produces a broad beam pattern. A quarter wavelength matching layer between the ceramic and the tissue was used to maximize signal amplitude. With this approach, much less care in placement of the transducers is required. The hemispherical transducers are, however, quite expensive, and construction of the matching layer is somewhat difficult.

Although the problems encountered are similar, the transducers used in cardiometry are not ideal for use in plethysmography. In particular, transducers used for plethysmography require a rugged housing and a convenient means of attaching the housing to the skin. In this report we describe the design and construction of transducers specifically designed for plethysmographic applications, and provide
details on the performance of these units.

Design Considerations

For attaching the ultrasonic transducers to the skin, it is convenient to use a housing of the same size and shape as that used with exercise EKG electrodes. The transducers may then be very simply attached with double-sided adhesive collars. With the size of the external housing determined, it is necessary to consider the optimum design of the transducer mounting within the housing. Both the hemispherical and the flat plate transducer designs have been mounted within the housing. We will first consider the flat transducer.

Small flat-plate ultrasonic transducers produce a wider beam, and the electrical impedance of ceramic transducers is reasonably low even for small transducers. Thus, for this application flat plate transducers should be as small as possible. For measurements across the calf, a transducer frequency of 2 MHz offers a convenient compromise between signal attenuation, which increases with frequency, and transducer thickness, which decreases with frequency. At 2 MHz the ceramic material is approximately 1 mm thick; the smallest disc which can be reproducibly cut from this material is about 3 mm in diameter. These considerations determine the size of the transducer element.

Because addition of a convex lens will diverge the beam pattern somewhat, it is desirable to include a lens in the design. If the lens is allowed to protrude into the tissue slightly, it will also serve to provide good acoustic coupling between the transducer and the tissue. The implementation of this concept is shown in Fig.21A, where a 3 mm diameter transducer is shown mounted behind a lens which
FIGURE 21. Design of Flat and Hemispherical Transducers
a 3 mm diameter transducer is shown mounted behind a lens which protrudes 3 mm into the tissue. The lens is mounted within the EKG housing to provide a space for attachment of the adhesive collars.

Hemispherical transducers may be mounted similarly within a housing of the same external shape as that used for the flat transducers. Because the hemisphere radiates in all directions, no lens is necessary; however, it is convenient to allow the transducer to protrude into the tissue to provide good acoustic coupling. Although hemispherical transducers are available in several diameters, there is no reason to expect significant differences in performance for different diameters. A more critical question is the design of the coupling layer between the crystal and the tissue.

Signal amplitude produced by an ultrasonic transducer may be increased somewhat by placing a quarter wavelength thick matching layer between the ceramic and the tissue [27]. This approach is routinely used in design of transducers for imaging applications [28]. In dimension gauges, however, signal levels are normally very high compared with those encountered in imaging; the wide beam pattern produced by hemispherical transducers enable strong signals to be obtained even when the crystals are badly misaligned. Thus, increasing the signal strength by several dB is of marginal value. The quarter wave length matching layer is very thin (<0.3 mm) and, thus, is difficult to fabricate and is subject to damage from abrasion. The capacitive coupling between the outer conductive coating of the crystal and the subject is large when a thin dielectric layer is used. The coupling can introduce high frequency noise into the system. For these reasons, the developed transducers use a coupling layer with a minimum thickness of 1 mm. Because this layer is more than one
wavelength thick, the second half-cycle of the received signal is not affected by reflections within the matching layer. Yet the layer is sufficiently thin so that attenuation within the layer is negligible. The implementation of this concept with a hemisphere of 12 mm diameter is shown in Fig. 21B.

Transducer Construction

Construction of the hemispherical receiver transducers is illustrated in Fig. 22. Three major elements are used to assemble the finished transducer. The plastic lens is molded from epoxy resin (STYCAST LN 78058, Emerson and Cuming, Canton, Mass.) in a machined teflon mold. After casting and curing, the back of this lens is machined with a ball mill to fit the hemispherical transducer. The transducer element is obtained commercially (Channel Industries, Santa Barbara, California) as a complete hemisphere. Teflon-insulated stainless steel leads (33 gauge, Cooner, Chatsworth, California) are carefully soldered to the inner and outer conductive coating of the crystal using a zinc chloride flux and ordinary solder. The crystal is then cemented into the plastic lens. A silastic tube is slipped over the leads. This assembly is mounted inside the pre-cast plastic exercise EKG electrode housing (Blackwell Plastics, Houston, Texas). The space between the plastic lens and the housing is sealed with non-corrosive silastic sealant (3140 RTV, Dow Corning Corp., Midland Mich).

Hemispherical transducers are available in several sizes, with the smallest being 6 mm in diameter with a resonant frequency of 3.8 MHz. Crystals resonant 2 MHz are available with a diameter of 12 mm and 9 mm. Any of these elements can be mounted within the lens
FIGURE 22. Construction of Receiver and Transmitter Elements
The housing of the flat transmitter transducer is accomplished in a similar manner. A 3 mm diameter disc is cut from a plate of LTZ-2 transducer material resonant at 2 MHz (Transducer Products, Inc., Gophen, Conn.). Leads are attached as before and the transducer is cemented into a cavity machined into the cast plastic lens. The assembly is then cemented into the plastic housing as before.

**Transducer Performance**

The external appearance of the developed transducers is depicted in Figure 23A. Fig. 23B shows the appearance of the transducers after attachment of the calf. Transducers are attached at two sites to allow simultaneous measurement of two chords. The adhesive collars provide a firm attachment which can be maintained for several days. Use of a very small quantity of acoustic coupling gel provides improved signal transmission in short-term attachment. For long-term experiments, gel is not necessary because normal skin secretions provide adequate coupling after several minutes attachment.

The most important characteristic of the transducer is the extent to which rotation off-axis reduces signal amplitude. Measured performance of the two transducer types is shown in Fig. 24. Two transducers were suspended in an acoustic test range, separated by 10 cm. In all tests a 3 mm diameter transducer was excited using a standard pulser to produce a constant acoustic signal. The transducer under test was connected to an amplifier having an input impedance of 50 ohms. The tested transducer was rotated in 5 degree increments and beam strength was determined by adjusting a calibrated attenuator to return the amplitude of the second half-cycle to the level obtained at
FIGURE 23. The Developed Ultrasonic Transducers
A. 3 mm DIAMETER FLAT TRANSDUCER

B. HEMISPHERICAL TRANSDUCER

FIGURE 24. Off Axis Performance of Transducers
0 degrees. As expected the flat transducer is quite directional. The response of the hemispherical transducer is unaffected by rotation over the range of +40 to -40 degrees. Fall off of the response beyond this angle is probably due to interference within the plastic lens. The beam width of the hemisphere could be improved by protruding the lens further, but this would cause unnecessary distortion of the tissue and possible discomfort to the subject.

The directional characteristics of the transducers is further demonstrated in Fig. 25, where recorded pulses are shown. With the flat transducer the pulse shape remains unaltered with rotation, but the amplitude decreases sharply. The pulse shape of the hemispherical transducer is more complex, and changes with rotation; however, the amplitude and shape of the first cycle of the received pulse are almost unaffected by rotation. Because pulse arrival is determined by triggering a comparator on the second half-cycle of the received pulse, the remainder of the pulse is unimportant for plethysmographic applications.

In design of associated electrical circuitry, knowledge of the electrical behavior of the mounted transducers is necessary. Impedances of the two transducer types were measured in air, using an impedance meter (HP model 4815A). The flat transducer, because of its smaller size, presents a relatively large impedance (approximately 800 ohms at resonance) and behaves as a much more reactive (capacitive) load. The hemispherical transducer displays an impedance of only 80 ohms and behaves as a nearly resistive load at resonance. At very high frequencies the impedance of both transducers decreases sharply due to the parallel capacitance of the crystal.
FIGURE 25. Directional Characteristics of Ultrasonic Transducers
Use of the Transducers

Although these transducers may be used interchangeably as receiver and transmitter, when the two are used in combination it is often convenient to use the flat transducer as a transmitter and the hemisphere as a receiver. Because of the high voltage and current required, changing impedance and voltage levels in the pulser requires extensive redesign of the circuit. The low impedance of the hemispherical transducer at high frequencies may load the pulser of some dimension gauges excessively. The flat transducer, however, will produce negligible loading. On the other hand, when the hemisphere is used as a receiver, the low impedance of the hemisphere can easily be matched to the higher impedance of the RF amplifier by use of the step-up transformer, producing a higher voltage input. The low impedance of the hemisphere allows use of the relatively long cable without significant capacitive loading of the transducer.

The use of two hemispheres provides most freedom in placement of transducers when a sufficiently low-impedance pulser is used. This is illustrated in Fig. 26A, where signals passed though a calf of 38 cm girth are reproduced. To provide a reference for location of the transducer, the zero point of a cloth tape measure was attached to the leg at the sharp point of the tibia with the numbers increasing toward the inside of the leg. The tape was then wrapped loosely about the calf, and attached with adhesive tape. Positions of transducers were determined by recording the tape number nearest the transducer. Positions were then computed as angular deflections as if the cross-section of the calf were circular.

A hemispherical transducer was attached to the calf at 76 degrees
FIGURE 26. Comparison of Performance of Different Transducer Combinations
the lower edge of the tibia by palpation and then moving several cm down the calf. This location is optimum for the plethysmographic measurement: Placing the transducer further down the calf forces passage of the signal through the fibula; placing the transducer nearer to the tibia causes transducer movement to be restricted by the bone. The transmitting transducer was then placed at selected locations, as indicated in the Figure 26. Excellent signal quality was obtained as one of the transducers was moved over an 85 degree arc on the calf. The receiver amplifier is saturated on the second half-cycle of the received signal in each photograph.

In most situations the combination of a hemisphere as receiver with a flat crystal as transmitter provides very good results, although the range from which adequate signals can be obtained is smaller (Fig. 26B). Performance of this combination is due to the anatomy of the calf and the attachment procedure used. The receiver crystal (hemisphere) is first attached; the transmitter (flat) crystal is then placed against the opposite side of the leg and adjusted until maximum signal level is obtained. Thus, the directional transducer is adjusted until it is aimed at the receiver. This procedure is far simpler than would be the simultaneous adjustment of two directional transducers.

When flat transducers are used as both receiver and transmitter, signal quality is found to vary dramatically with small changes in transducer location. Small rotations of the transducer will also produce significant changes in the shape of the received pulse. These pulse shape changes are due to the narrow beam width of the flat transducers.
Both the combinations illustrated in Fig. 26 have been tested extensively both in short term physiological experiments and in long term attachment tests. Good signal quality is routinely obtained with minimal training of operators. In long-term attachment tests of up to 7 days no discomfort has been noted; signal quality is maintained so long as the transducers are firmly attached.
Summary and Conclusions:

The development of ultrasonic dimension measurement principles into a laboratory instrument providing plethysmographic data has been detailed in this report. The developed instrument has been compared with the Whitney strain gauge and on impedance measuring device and shown to yield consistent and reliable results.

In human subjects undergoing provocative maneuvers such as venous occlusion and tilt experiments the results have been shown to be repeatable and reliable. The major aim of this project was to develop instrumentation which freed the investigator from the transducer related problems of the capacitance plethysmograph and this was achieved. Since the developed plethysmograph uses transducers on opposite sides of the limbs, the integrity of movement is not compromised and also individualized transducer configurations are not required.

The transformation of the above instrument into a flight certified unit was carried out by Denver Research Institute. This unit has been fabricated and tested in accordance with the procedures developed in the report and is a part of NASA supplied LSLE item.
Theses, Dissertations and Publications:

The following theses, dissertations and publications resulted from the support derived from this research contract.

i. Murali P. Kadaba


x. Significance of phase of an ultrasonic pulse in tissue characterization, V. N. Gupta, P. K. Bhagat and A. M. Fried, Fifth Midwest Biomedical Engineering Conference and Workshop, Columbus, Ohio, May 30-31, 1980.


xiii. Vic C. Wu
"A microprocessor based ultrasonic limb volume measurement system." MSEE, 1980, Co-advisor with Dr. T. L. Henderson.

xiv. Vaikunth N. Gupta
"Ultrasonic tissue characterization via homomorphic transform." Ph.D., 1980.

xv. Ruth A. G. Dyer
"Classification and characterization of tissue pathology through ultrasonic signal analysis." Ph.D., 1980.


xvii. Ultrasonic properties of normal and functionally impaired renal tissue, V. N. Gupta and P. K. Bhagat. Sixth International Symposium on Ultrasonic Imaging and Tissue Characterization, Gaithersburg, Maryland, June 1-4, 1981.


xix. Mark Shafer
"The application of homomorphic processing to ultrasonic signals." MSEE, 1981, Co-director, Dr. B. J. Leon.


xxii. Ultrasonic quantification of skin and muscle hemodynamics, P. K. Bhagat, W. T. Nickell, and V. C. Wu, First Southern Biomedical Engineering Conference, Shreveport, Louisiana,
June, 1982.


APPENDIX A

Background Data on Transducers

A. Piezoelectric material properties

Ferroelectric crystals are among the ceramic materials which do not have identical centers of positive and negative charges. A necessary but not sufficient condition for a solid to be ferroelectric is the absence of a center of symmetry of electrical charges. This type of material such as quartz, either elongates or contracts upon the application of an electric field. This dimensional change is due to the effect of the applied electric field on the dipole length. Such behavior in the ferroelectric material provides a means of converting electrical energy into mechanical energy. The crystal vibrates with the frequency of applied alternating field and in proportion to the voltage differential. This property of ferroelectric materials of dimensional changes upon the application of an electric field has led to the electro-mechanical transducer devices, which are commonly used for the production of high frequency sound waves.

In piezoelectric material the converse effect exists, i.e., upon the application of mechanical stress to the crystal, an electric potential is produced which is proportional to the applied stress. There are 21 classes of crystals which can be classified as ferroelectric material (24). Twenty of these materials are piezoelectric, i.e., they exhibit the converse effect too. Some commonly used piezoelectric ceramics are barium titanate (BaTiO$_3$) and lead zirconate (PbZrO$_3$).

Ferroelectric ceramics are spontaneously polarized material.
This polarization is dependent on the temperature at which the material exists. The transition from ferroelectric to nonferroelectric occurs at a temperature called the "Curie point". Barium titanate (BaTiO$_3$) has a stable cubic structure above 120°C. At room temperature it changes to a tetragonal structure, thus producing a polarization due to the movement of the titanium ion (Ti$^{4+}$). Such movement of the titanium ion (Ti$^{4+}$) introduces an electrical charge imbalance into the unit cell. There is the probability that the titanium ion would be located in one of two locations along one of the major axis (x, y, or z). Since neither location is at the center of the unit cell the center of negative and positive charges are not coincidental and an electrical dipole must exist. The movement of the titanium ion to the second location by a neighboring polarized unit cell is possible, since the energy barrier between the two possible sites along one axis is low. This is known as the cooperative alignment of unit cells, which gives rise to electrical domain in the ferroelectric material as shown in Figure 27.

Upon application of an external electrical field the ferroelectric material domain, will follow the polarization of the applied field, and dimensional changes in the material will occur due to a change in the dipole orientation in the unit cell. Therefore, if an alternating electrical field was applied, vibration of the crystal will take place and ultrasound waves will be generated.

Mason (25) noted that dimensional changes in piezoelectric crystals are dependent on the polarity of the applied electric field and the crystal orientation. He deduced that the piezoelectric properties of a crystal are anisotropic and depend on its orientation. Piezoelectric properties of a crystal are usually described by
a) Schematic Representation of Cooperative Alignment of Unit Cells

b) The Domain in Ferroelectric Materials

FIGURE 27. Domain Alignment in Ferroelectric Materials
certain parameters. Since these properties are direction-dependent, indices are usually used to specify each individual parameter. Some of the important parameters which pertain to the selection of a piezoelectric crystal for a specific application are listed below:

1. Transmitting Constant $d_{ij}$
   Defined as the strain produced in a transducer by the application of a unit electric field, and has the unit of coulomb/newton.

2. Receiving Constant $g_{ij}$
   Defined as the electromotive force produced in a crystal upon the application of a unit pressure input, and has the unit of $\frac{\text{volt/meter}}{\text{newton/}(\text{meter})^2}$.

3. Deformation Coefficient $h_{ij}$
   Obtained by multiplying the receiving coefficient by Young's Modulus of the crystal for a specified direction. It has the unit of newton/coulomb.

4. Coupling Factor $k_{ij}$
   Provides a measure of the crystal as an energy converter.
   \[ h = (h_{ij}d_{ij})^{1/2} \]

5. Permittivity Constant $\varepsilon_{T,S}$
   The dielectric constant representing the permittivity of the material, and how much current is flowing through for each volt. The units of $\varepsilon_{T,S}$ are farad/meter. For this constant, the value of $\varepsilon$ for the crystal is different in the clamped ($\varepsilon^S$) than the free ($\varepsilon^T$) state (25).

6. The Mechanical Factor $Q_m$
   Determines the frequency characteristic of the crystal. This factor is independent of the geometry of the crystal, and is a
measure of the frequency band width:

\[ Q_m = \frac{f_0}{f_2 - f_1} \]

\( f_0 \) = Resonance frequency

\( f_1 \) = frequency below resonance for a reduction in amplitude of 3 db.

\( f_2 \) = frequency above resonance for a reduction in amplitude of 3 db.

B. Ultrasonic Field

When an ultrasonic transducer is excited, waves are generated and travel in the immediate medium surrounding the transducer. A pressure distribution with maxima and minima is created in the medium. This is called an ultrasonic field. Fig. 28 is a schematic representation of the field for a circular disk transducer. Positions and amplitudes of the extrema in the ultrasonic field depend greatly upon the ratio of the surface dimensions of the source to the wave length produced.

There are two distinctive regions in the ultrasonic field which are of importance in the design of the transducer. The two regions are: The Fresnel Region (nearfield) and Fraunhofer Region (farfield).

1. The Fresnel Region

The Fresnel Region is also known as the near field. Its depth for circular transducer is given by:

\[ x = \frac{d^2}{4 \lambda} \]

where:

\( d \): disk diameter

\( \lambda \): wave length.

\( x \) corresponds to the last axial maximum pressure which is the end of Fresnel zone and the beginning of Fraunhofer zone. For a complete mathematical treatment of this region, see Hueter and Bolt (26).
FIGURE 28. The Ultrasonic Field of Circular Disk Transducer

Equation for the nearfield: \[ \frac{I}{I_0} = \sin^2 \left[ \frac{\pi}{\lambda} \sqrt{r^2 + x^2 - x} \right] \]
2. The Fraunhofer Region

The ultrasonic field generated by a circular disk transducer had the shape of a cylinder in the nearfield region. At the beginning of the farfield region the ultrasonic beam starts diverging from a uniform cylinder shape. The angle of the beam divergence from a cylindrical shape is given by:

$$\sin \theta = \frac{0.61(2\lambda)}{d}$$

(11)

And for a square transducer is given by:

$$\sin \theta = \frac{\lambda}{t}$$

Where \((d)\) is the disk diameter and \((t)\) is the width of the crystal. In this region the intensity of the wave is reduced sharply due to the divergence effect, and this will affect the attenuation measurement in the far field region.

C. Measurement System

We have developed a microprocessor based ultrasonic data acquisition and analysis system for measurement of acoustic parameters of a given sample \((19, 23)\). This system was used for measurement of transducer beam profile and central axis intensity as a function of distance.

Instrumentation details:

The main components of the developed pulse-echo system are shown in a block diagram in Fig 29. The system consists of a pulse generator, radio frequency (RF) receiver amplifier, calibrated attenuator, and a peak detector. A range gate enables the selection of a particular segment of the reflected signals for processing. All
Figure 29. Data collection and analysis block diagram
of the above are housed in a single unit (Aerotech Labs, UTA-3). The input receiver sensitivity is 5 mV with a frequency bandwidth of 24.6 MHz and a lower frequency cutoff at 400kHz. The receiver gain is 40dB with an output impedance of 50 Ω. A second set of pulser, receiver, and range gate (Metrotek, Inc.) was utilized in some experiments primarily due to the higher value of excitation (adjustable up to 230V) delivered by the pulser. Acquisition of a microprocessor (Altair 8800), a high speed A/D convertor (Biomation 8100) and an off line minicomputer (PDP 11/34) facilitates digitization and storage of rf signals on a disk for further processing. Accurate transit time measurements can be accomplished using a 225 MHz universal counter timer (Textronix 7B15). Spectral analysis of data can be performed in analog fashion using spectrum analyzer (Tektronix 7L13) or digitally using standard Fast Fourier Transform (FFT) routines available on the DEC LAB applications package.

Mechanical Apparatus

The mechanical apparatus used in this project, shown in Figure 30, was designed and assembled in our laboratory. The acoustic test tank is made of clear, 1.25-cm thick plexiglass, and is lined with a sound-absorbing Styrofoam sheet to prevent any extraneous reverberations caused by multiple reflections. The test tank is filled with degassed distilled water, which acts as the coupling medium between the ultrasonic transducer and the specimen. The transducer holders are made out of plexiglass and are mounted on a sterotaxic positioning device, which provides several degrees of freedom for accurate positioning of the transducer. Thick plexiglass slabs of various geometries were

---

1 Subsidiary of KB-Aerotech, Lewistown, PA.
2 Metrotek, Inc., Richland, WA
used as reflectors. A 1-rpm synchronous motor is used to control the angular orientation of the transducer with respect to tissue sample.

The mechanical scanner consists of two motor-driven slide assemblies capable of movement in a longitudinal direction, as well as in a transverse direction. The linear velocity of the slides may be separately controlled. The slides have a maximum displacement of 30 cm in the longitudinal direction and 5 cm in the transverse direction. Analog position indicators were incorporated to indicate the position of the scanning transducer with respect to a reference coordinate frame. The whole assembly is made of Duralmin. A calibrated hydrophone (Mediscan, Inc.) with a crystal diameter of 0.7 mm is used as receiver to scan the beam. The scanning is carried out at various axial distances from the transmitting transducer and covers the entire transmitting cross section.

D. Piezoelectric transducer material used in this study.

The transducers used in this project were made from two types of piezoelectric material, LTZ-2 and LTZ-5. (Transducer Products, Inc.). The material is available in form of squares (l", l", t) where t is the thickness which varies to yield different resonance frequencies. The specification for the material are as follows:

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>LTZ-2</th>
<th>LTZ-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{33}$</td>
<td>25.5*10^3</td>
<td>35.2</td>
</tr>
<tr>
<td>volt/m/N/m^2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d_{33}$, m/volt</td>
<td>405*10^{12}</td>
<td>155*10^{12}</td>
</tr>
<tr>
<td>$Q_m$</td>
<td>75</td>
<td>500</td>
</tr>
</tbody>
</table>

For application in ultrasonic plethysmography either material type has been observed to be suitable.
APPENDIX B

Test Procedure and Results Using Prototype ULP

Introduction

The Ultrasonic Limb Plethysmograph, fabricated by Denver Research Institute, was received by the Wenner-Gren Research Laboratory (WGRL) on May 20, 1981. Tests were carried out in accordance with the test plan developed by WGRL in consultation with Clete Booher of NASA. Personnel involved in the testing program were: P. K. Bhagat, V. C. Wu, W. T. Nickell, Dave Brewer, Mark Shafer, and WGRL support personnel. Results of these tests are presented in the following pages.
A. PHYSICAL EXAMINATION

I. External Dimensions (LxWxH): 18.2 cm x 11.4 cm x 5.08 cm
   Weight (kg): 1.173 kg  Batteries (kg): 0.114 kg

II. Connectors. Are all external connectors:
   a. Sufficiently secure to ensure reliable electrical contact? Yes
      Comment:
      A marker is needed on the female connector to facilitate correct insertion.
   b. Rapidly disconnected in an emergency? X
      Comment:
      Connection appears to be tight. It should be verified by NASA.

III. Are there sharp edges on the case? X
      Comment:
      When cassette door is opened, sharp edges are exposed on the door and the locking mechanism.

IV. Check rigidity and security of indicated parts:
   a. Case O.K.
   b. Batteries X
      Comment:
      1. Banana jack needed tightening.
      2. Not easy to change batteries.
      3. Needs a cover to prevent accidental operation of the switch on the cartridge. Recommend a supply of spare cartridges be provided with the unit.
   c. LCD Assembly O.K.
   d. Electronic Cards X
Comments:

1. PC board need cleaning.
2. Unused switch on the tape recorder needs to be covered.
3. Battery and tape recorder power supply wires need to be harnessed or secured.
4. The real time clock battery holder spring needs to be modified so as to prevent short circuit of the battery.

V. Shake the unit. Are any unusual sounds produced? Yes

Comment:

Cassette is not securely mounted. Cassette strap ring should be removed.

VI. Is the LCD display readable? Yes

VII. Tape Drive

a. Does the tape drive motor produce an abnormal noise level? No

b. Operate the tape removal and insertion mechanism. Is performance satisfactory? Yes

c. Is 'rewind' switch operation satisfactory? See comments

Comments:

1. The door does not provide easy access to the rewind switch. Suggest additional clearance when door is opened (modify hinges).
2. When the door is closed, movement of the recorder switch to "Stop" position should be prevented.
3. Operation of door closing mechanism is difficult.

IX. Check materials included in prototype against materials list.

Mechanical Listing

1. Toggle switch movement shown in drawing ED-14843 is 90° off prototype position - Change the drawing.
2. Prototype fitted with Phillip screws. Drawing ED-14843 shows straight screws.
3. Items in the drawings should specify all parts. For example, Item 7 in ED-14843 should specify both push button switches.

Needs electrical parts listing and materials used list.

IX. Can all indicator lights be seen under normal ambient light levels? Yes
Color as required? Yes

Comment:

When the tape is full, there is a warning sound. This sound should be approved by NASA for operational convenience. Audibility of this sound under Spacelab condition should be checked by NASA.
B. ELECTRONIC TESTS

I. Circuit diagram review. Carefully review the units circuit diagram.
   a. Is item complete? Yes
   b. Is circuit satisfactory? See comments

Comments:
   i. Symbols not consistent - example LED
   ii. Core and size of transmit transformer not defined.
   iii. Receiver transformer ratio not defined. Suggest using the receiver transformer for impedance matching between transducer and amplifier input stage.
   iv. Pin 16 of hybrid ED-15236-2 is not defined.
   v. The signal quality test light is amber instead of red as shown in drawing.
   vi. In EC-15033 and ED14401, a bigger DIP package than needed is used.
   vii. Size and type of plug should be defined for DRS power control jack and DRS "MIC" jack (EC-14402).
   viii. Capacitor on pin 7 of power supply hybrid not labeled (EC-14402).
   ix. Pin 17 test point not identified in the drawing EC15019.

II. Functional Test. Place a transducer set in a water bath. Verify that instrument works, using LCD display as output.
   a. Stability O.K.
   b. Accuracy O.K.

Comments:
   a. Up to 1 mm fluctuation in display.
   b. 24 ±1 counts/2 mm

III. Quality of output signals. Conduct these measurements with power supply voltage at lowest specified value. Photograph signals using oscilloscope and camera.
   a. Output pulse. Measure with 50 ohm termination.

   Amplitude? 5V P-P
   Rise Time? 35 ns
b. Frequency content. Determine power spectrum of pulse.

See Attached Drawing

Amplitude? 

Rise Time? 

c. Output pulse. With transducer attached.

Amplitude? 67V.P-P
Rise Time? 50 ns

d. Digital output. Measure using expected logic termination.

Amplitude? 5V.P-P
Pulse Shape? O.K.
Noise? O.K.

See next pages for graphs and pictures.
Transmit Transformer output with 50Ω (using Biomation)

With Transmitter (Captured on Biomation)

FIGURE 31: ULP Transducer Output Pulse Shape
FIGURE 32. Digital Output in EDI Mode (2400 Baud)
FIGURE 33. Output Pulse with 50 Ω Termination
FREQUENCY CONTENT OF OUTPUT PULSE
WITH 50 OHM TERMINATION

X TIC INTERVAL = 5 MHz
Y TIC INTERVAL = 6 DB.

FIGURE 34. Amplitude Spectrum of the Output Pulse
FIGURE 35. Pulse Shape with Transducer Load
IV. Receiver and Trigger. Conduct these tests with lowest permitted supply voltage.

a. Receiver amplifier Gain
   Acceptable? 
   $53\text{db}$

b. Noise level of receiver.
   Acceptable? 
   $50\text{mVRms}$

c. CMRR of Receiver
   Acceptable? 
   $>20\text{db}$

d. Threshold stability of trigger.
   Acceptable? 
   Yes

e. Input Impedance of receiver. Measure input impedance of receiver between 450 kHz and 10MHz.
   Data enclosed. Resonance occurs between 1.5 and 2 MHz (Phase Change) - Measured using vector impedance meter.

   $50\text{kHz and } -5.5\text{MHz}$
   Comment:
   Measured using differential sine wave input.

g. Determine range of transmitter - receiver combination, as compared with original ULVS unit.
   Minimum - 6.1 cms, Maximum - 24 cms
   Comparable? 
   Yes, but the minimum is higher than the original ULVS unit.
## ULP Receiver Impedance

<table>
<thead>
<tr>
<th>FREQ. (MHz)</th>
<th>IMPEDANCE (Ohms)</th>
<th>PHASE ANGLE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>INPUT 1</td>
<td>INPUT 2</td>
</tr>
<tr>
<td>0.5</td>
<td>370</td>
<td>380</td>
</tr>
<tr>
<td>1.0</td>
<td>1.05K</td>
<td>1.05K</td>
</tr>
<tr>
<td>1.5</td>
<td>3.0K</td>
<td>4.3K</td>
</tr>
<tr>
<td>2.0</td>
<td>3.0K</td>
<td>2.9K</td>
</tr>
<tr>
<td>2.5</td>
<td>1.4K</td>
<td>1.35K</td>
</tr>
<tr>
<td>3.0</td>
<td>950</td>
<td>920</td>
</tr>
<tr>
<td>3.5</td>
<td>720</td>
<td>710</td>
</tr>
<tr>
<td>4.0</td>
<td>600</td>
<td>580</td>
</tr>
<tr>
<td>4.5</td>
<td>500</td>
<td>480</td>
</tr>
<tr>
<td>5.0</td>
<td>430</td>
<td>420</td>
</tr>
<tr>
<td>5.5</td>
<td>380</td>
<td>370</td>
</tr>
<tr>
<td>6.0</td>
<td>340</td>
<td>335</td>
</tr>
<tr>
<td>6.5</td>
<td>310</td>
<td>300</td>
</tr>
<tr>
<td>7.0</td>
<td>280</td>
<td>280</td>
</tr>
<tr>
<td>7.5</td>
<td>260</td>
<td>260</td>
</tr>
<tr>
<td>8.0</td>
<td>240</td>
<td>235</td>
</tr>
<tr>
<td>8.5</td>
<td>220</td>
<td>215</td>
</tr>
<tr>
<td>9.0</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>9.5</td>
<td>195</td>
<td>195</td>
</tr>
<tr>
<td>10.0</td>
<td>185</td>
<td>180</td>
</tr>
</tbody>
</table>
Comment:

1. Due to the design of the testing pad additional noise is introduced into the receiver output. For this reason, the numbers listed above do not reflect actual values.

2. The actual receiver gain is lower than that specified in the end item specification. However, operation appears to be satisfactory.

V. Function switches. Check function of switches.

a. Time Set O.K.

b. Time on/off O.K.

c. Fast/slow O.K.

d. Self-test/Reset O.K.

e. Power O.K.

Comment:

i. Operation of 2 or 4 chord switch has no effect until 'Reset' is operated.

ii. Access to function switches is difficult due to their location under the tape recorder. Suggest vertical mounting of the switches for ease of operation.

VI. Automatic signal quality check.

Does automatic signal quality check system perform properly? Yes

Describe measurements made to verify operation of this function:

Transducers 100 mm apart were placed in a water bath.

a. One of the transducers was rotated until poor signal quality was apparent. The warning light indicated this condition correctly.

b. Keeping one of the transducers fixed, the other was given sinusoidal displacement at varying rates. When the amplitudes and frequencies of 5 mm, 0.5Hz; 2.5 mm, 0.7Hz and 1.0 mm, 1.6 Hz were exceeded the warning light was 'ON' even though the signal quality was good.
The warning light sometimes is on during physiological tests even though the quality of signal is good. Suggest changing the test range of signal quality.

VII. Power Consumption. Measure average steady state power consumption using series ammeter and volt meter.

- **a. Slow Mode**
  - 179-182 ma, 7V 2 chord
  - 182-186 ma, 7V 4 chord

- **b. Fast Mode**
  - 172 ma, 7V 2 chord
  - 176-180 ma, 7V 4 chord

- **c. Recorder Running**
  - 167 ma, 7V 2 chord
  - 120 ma, 3.5V 2 chord

For 4 chords, the numbers are essentially the same.

- **d. Battery Life Under Normal Operation from full charge.** 33 hrs.

Comment:

Out of spec conditions on voltage were observed on two occasions. Suggest recheck of power supply hybrid.

IX. Time Base Accuracy

- **a. Clock Frequency** 18.0042 MHz, 60.0014 Hz

- **b. Determine clock Accuracy by test against official standard.**

  Drift was 6 seconds for four days and 37 seconds for twenty days when tested against WWV.

<table>
<thead>
<tr>
<th>Initial Readings</th>
<th>Standard</th>
<th>ULP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 week</td>
<td>_____</td>
<td>_____</td>
</tr>
<tr>
<td>1 month</td>
<td>_____</td>
<td>_____</td>
</tr>
</tbody>
</table>

IX. Tape Operation

- **a. Quality of Recorded Signal**
  - Amplitude O.K.
  - Noise Level O.K.
Stability  

See attached data on page .

b. Interface to LSLE computer. Comment on any problems encountered:

Interference between EDI data output and receiver input was observed, however, rearrangement of external wire eliminated this problem. We feel that EDI output sometimes feeds signals to the receiver amplifier during data transmission.

c. Data Reliability. Record a string of at least 5,000 data points. Play recorded data into LSLE computer. Determine number of transmission errors which occur.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Error Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow Mode</td>
<td>1 error</td>
</tr>
<tr>
<td>Fast Mode</td>
<td>NONE</td>
</tr>
</tbody>
</table>

Comments:
FIGURE 36. Tape Recorded Signal Played Back with 1K Load and Capture by Biomation A/D Converter.
C. USE TESTS

I. Ease of use. Attach the unit to an experimental subject. Instruct subject to operate controls, change tapes, conduct simple exercises, and remove and reattach the unit.

a. Accessibility of Controls O.K.
b. Visibility of Indicator Lights O.K.
c. Ease of Changing Tape and Battery

See section A, IV b of this report.
d. Difficulty in detaching or reattaching cables and connectors

See section A, II of this report.
e. Comfort

Comments:

Need 'pouch' to comment on comfort.

II. Provocative Tests. Conduct Venous Occlusion and tilt-table tests to produce changes in limb volume.

a. Transmit data directly into LSLE microcomputer

Quality of Data O.K.

Interpretation of Data O.K.

Comments:

More noise spikes on 2nd chord. Does not seem to be on transducer. The problem is intermittent. Data enclosed.

b. Record data on tape.

Quality of Data O.K.

Interpretation of Data O.K.

Comments:

Data enclosed on pages 99, 100 and 101.
FIGURE 38. Time Course of Limb Dimension Changes Under 50° Head Up Tilt
FIGURE 39. ULP Data Played Back from the Recorded Venous Occlusion (50 mmHg) Data

V.O. CHORD 1

V.O. CHORD 2

T.T. CHORD 1

T.T. CHORD 2

ULP RECORD Mode TEST
X-Y TIC INTERVAL = 1 MIN.
Y TIC INTERVAL = 5 COUNT.
III. Routine Monitoring. Use tilt-table to produce leg volume data over a 30 minute period.

   Quality of Data  O.K.
   Ease of Interpretation  O.K.

Comments:
Data enclosed on page 103.

IV. Automatic signal check. Use automatic signal check feature to place transducers on subjects leg. Verify quality of signal using oscilloscope.

   # trials/# correct  O.K.

Comments:
FIGURE 40. Passive Monitoring of Data Through a Tilt Table Experiment
CHORD 1

ULP ROUTINE MONITORING TEST
X TIC INTERVAL = 1 MIN.
Y TIC INTERVAL = 5 COUNT

CHORD 2

FIGURE 40. (Continued)
TEST EQUIPMENT USED IN EVALUATION OF ULP

1. Biomation, Model 8100, Transient Recorder
2. Tektronix, 604, Monitor
3. Tektronix, SC 502, Oscilloscope
4. Hewlett-Packard, 7402A, Strip Chart Recorder
5. Fluke, D802 Multimeter
6. Fluke, 8020A Multimeter
7. ULVS, Wenner-Gren Research Laboratory
8. OHAUS, Harvard Trip Balance
9. Wavetek, HF Sweep Generator, Model 144
10. Tektronix, 7633 Multimode Storage Oscilloscope, with plug-in units, 7A26 Dual Time Trace Amplifier, 7D15 225 MHz Universal Counter/Timer and 7B53A Dual Time Base
11. Hewlett-Packard, 4815A RF Vector Impedance Meter
12. Tektronix, 4051 Graphics System With 4051E01 Rom Expander
13. Tektronix, 4662 Interactive Digital Plotter
14. Tektronix, P6202 Probe
15. Tektronix, C-5B Oscilloscope Camera
16. Hewlett-Packard, 5303B Frequency Counter
17. Velmex, Series B2500, Positioning System
18. Velmex, Model 311, Control Unit
19. La Berne Tilt Table
20. MTS 442 Controller
21. Cromemco, System Three, Computer
22. MTS Servoram
23. LAMBDA LH-124 FM, D.C. Power Supply
24. RCA WP-702A, Dual D.C. Power Supply
Conclusions and Recommendations

The basic design of the ULP unit is sound. Most problems encountered in our testing program were operational difficulties which can be fixed by either modifications of software and/or development of proper procedures. The following specific recommendations are made:

1. RF signal cannot be seen on a conventional oscilloscope because of the low repetition rate. This makes transducer placement very difficult without the original ULVS. Software fix is needed to provide at least 100 sweeps/sec.

2. We have had some problems with the automatic signal quality check. It is sometimes 'ON' when the signal is good and 'OFF' when the signal is bad. Resetting the levels might cure the problem. We suggest calculation of power requirement of the Automatic Signal check. The signal quality check could be made only once every 10 sec., for example if this would save power. In addition, the maximum sampling rate could be increased.

3. Polarity of the leads is a problem. The first 1/2 cycle of a "good" signal is normally small. It is desirable to trigger on the 2nd half cycle. With the ULVS this problem is handled by reversing polarity. The leads should be designed so that the polarity can be set using an oscilloscope and recovered when leads are reattached.

4. The receiver transformer needs further work. The turns ratio should be set to match transducer impedance to receiver impedance. The transformer does not behave in an ideal manner over the important frequency range. There is a resonance between 1.5 and 2.0 MHz. We suggest consultation with WGRL or purchase of
commercial units. Improvement of the transformer design will probably improve the receiver gain significantly.

5. Transmitter pulse width is long compared with the natural period of the transducer; the pulse is bipolar. This might cause problems if a higher frequency transducer were to be used.

6. The size and weight of the unit are slightly above specifications. We offer the following suggestions for reducing these values:
   a. The present case is made of very thick material. Size and weight could be reduced significantly by using a less substantial case.
   b. The tape recorder case, the replay electronics, and the speaker are superfluous. Space and weight could be saved by removing these components.
   c. A more compact shape might be produced by careful arrangements of parts. Unfortunately, the length and width of the unit are set by the size of the PC board. Placement of the circuit on two PC boards would allow a more compact shape to be produced.

7. The gain of the receive amplifiers is slightly lower than that of the original ULVS. Increasing the gain by a factor of two would improve device performance.

8. Turning the unit 'OFF' causes loss of data back to the last tape recorder dump. This will be an operational inconvenience in some cases. The software should be written so that the ULP stops recording data when the transducers are disconnected. This would allow the power switch to remain 'ON' for long periods without draining the batteries significantly.
APPENDIX C

Description of Individual Circuit Blocks of Two Transmitter ULVS

A. Processor, Memory and Display

This block (Fig. 41) consists of one Intel 8080 CPU, two 2708 EPROMs for storage of instruction codes and constants, two 2111 RAM chips for storage of generated data, one 8228 data bus and status controller, and an 8224 clock generator which provides the working clock at 2 MHz for the CPU and also supplies the clock frequency for the counter at 18 MHz. It also contains a 6820 Motorola PIA which drives four BCD to seven segment decoders/drivers 7448, which in turn drive 4 DL-704 common cathode LED's where the results are displayed. The 5th digit of the LED display is wired so that it will show blank or "1" only; this digit is driven by an npn-transistor which is controlled by line CB2 of the 6820 PIA. Two 7400 NAND and one 7402 NOR gates are used to provide the required address decoding. They also provide suitable enabling signals. Because the 8080 has both memory reference and I/O reference instructions, the circuit is arranged so that the 6820 occupies I/O addresses 04 to 07 of the CPD (address 00 to 03 is reserved for the use of the other 6820 which will be discussed later). The two 2708 ROM chips use memory addresses from 000 to 7FF Hex. Two 2111 RAM chips then occupy memory addresses from 800 Hex to 8FF Hex. The decoding and enabling logic of each peripheral chip is implemented as follows:

Chip Select of 2708 (1) = All + MEMR . A10
Chip Select of 2708 (2) = All + MEMR . A10
Chip disable of 2111 (1), 2111 (2) = All
Output disable of 2111 (1), 2111 (2) = MEMR
Read/Write of 2111 (1), 2111 (2) = MEMW
Chip Select 0 and 1 (CS0 and CS1) of 6820's = 1
Chip Select 2 (CS2) of 6820 (2) = A2
Chip Select 2 (CS2) of 6801 (1) = \overline{A2}
Enable of 6820's = IOW + IOR
Read/Write of 6820's = IOR

Where AO to All are address lines from the CPU, and MEMR, MEMW, IOR, and IOW are signals from the 8228. These signals represent memory-read, memory-write, input/output read, and input/output write respectively. Note that in order to simplify the decoding circuit, non-fully-decoded addressing is used.

The Intel 8080 microprocessor serves as the CPU of the system. The two clocks, \( \mathcal{O}_1 \) and \( \mathcal{O}_2 \), the reset, ready, and synchronizing signals are all provided by the 8224 clock, which controls the timing for the entire system. An 18 MHz crystal is connected at pins 14 and 15 of the clock and the resulting oscillatory output is available at pin 12 to run the counter in the next block (see Figure 42). An external reset button is connected between the Reset Input (Resin), Ready Input (Rdyin), and ground to allow manual reset of the system. The status strobe (STSTB) is connected to the 8228 Data Bus (Pin 1, STSTB) to synchronize its operation.

The 8228 Data Bus and Status Controller is used to increase the driving capacity of the CPU. It generates all signals required to directly interface RAM, ROM, and I/O components. It also provides isolation of the 8080 data bus from memory and I/O which allows for the optimization of control signals. The isolation of the bus driver also provides for enhanced system noise immunity. Data lines D0 to D7 of the 8080 are tied to D0 to D7 respectively of the 8228. The Write...
FIGURE 42 - Schematic of controller logic, transmitter select and counter for two transmitter ULVS
(WR), Data Bus in (DBIN) and the Hold Acknowledge (HLDA) lines of the 8080 are tied to the corresponding lines, WR, DBIN, and HLDA of the 8228. The DBIN signal indicates to external circuits that the data bus is in the input mode. The HLDA appears in response to the Hold signal and indicates that the data and address bus will go to the high impedance state. Line 22, BUSEN, is the bus enable input. It is tied to ground to keep the data bus always enabled. The output of the 8228 are lines DBO to DB7, the extension of 8080's data lines. These data lines are then available to the peripheral components. This provides a two-way data path with high fan-out between CPU and external components. Four other output lines of the 8228, Memory Read (MEMR), Memory Write (MEMW), I/O Read (IOR), and I/O Write (IOW) are available to control read/write operations in other components.

Memory capabilities of the system include two 256 x 4 RAM and two 1k x 8 ROM chips. Input/output data lines of the two RAMs (pins 11-14 of both chips) are tied to the Data lines DBO-DB7 of the 8228 to allow data transfer between the CPU and RAM. Each RAM has its address line AO-A7 tied to AO-A7 of the 8080 to enable the CPU to store and read data at specific addresses in RAM. Read and Write enabling signals come from the MEMR and MEMW lines of the 8228. Input/output data lines of each ROM (pins 9-11, 13-17 of each chip) are also tied to the Data lines DBO-DB7 of the 8228 to allow data transfer between the CPU and ROM. Each ROM has its address lines AO-A9 tied to AO-A9 of the 8080 to enable the CPU to read data from specific addresses in the ROM. Each memory chip is located at the addressable location stated above.

A 6820 Peripheral Interface Adaptor (PIA) is included to
facilitate efficient data transfer of the computed limb cross-sectional area to the display. Data lines of the 8228 are tied to the corresponding data lines to the PIA and when the area has been computed, the PIA reads in the data. The data is then output from lines PAO-PA7 to the 7448 BCD-to-seven segment decoders, whose output goes to the seven segment displays. Read and write signals for the PIA are supplied by the IOR and IOW lines of the 8228 respectively. A Reset signal is supplied by 8224 clock. The PIA is located at the addressable memory locations stated above. Switching in all circuits is controlled by the program in 8080.

B. Controller Logic, Transmitter Select, and Counter

The function of this block (Fig. 42) is to control the flow of information throughout the system, to select a transmitter for chord length measurement and to provide a count proportional to measured ultrasonic transit time for further computation. It contains a 6820 PIA which drives three cascaded 4-bit 7493 binary counters, a CD4052 analog switch, a 7474 D-type flip-flop, a 74121 one shot, and 7400 NAND chip for logic level converting and gating between the binary counters, flip-flop, one shot and the analog switch.

The PIA in this block is used to interface the binary counters with the CPU, and it is connected almost in an identical manner to the previous PIA (Fig. 41). Data line DO-D7 (pins 26-33) as well as reset, enable, read/write, RSO, and RSI (pins 34, 25, 21, 36, and 35) are all connected as described earlier. The only difference is the chip select 2 (CS2) pin. This allows the CPU to select one or the other of the PIA's. Lines PAO-PA7 and PBO-PB3 are connected to the output of the 7493 binary counters as shown in Fig. 42, in order to allow the CPU access the binary count. The three counters are
connected in cascade such that the least significant bit of the count is output at pin 12 of the 7493 #1 and the most significant bit is output at pin 11 of the 7493 #3. The counting frequency is supplied of by the 8224 clock (Fig. 41) and is connected to pin 14 of the 7493 #1. Counting frequency is 18 MHz, hence the accuracy of time measurements is 55 nsec. The counters are enabled by a 7474 D-type flip-flop.

The 7474 is set by the transmitter enabling pulse from the CPU through the PIA at line PB7. Pin 4 of the flip-flop is the reset. Initialization of the counters is provided by the output, Q, of the flip-flop. Q and the 18 MHz pulse from the 8224 clock are input to a 7400 NAND gate, and the output is used to enable the counter and control its counting frequency. Pin 1 of 7474 is the clear input, and it is connected to the receiver's comparator output in order to stop the counters when the signal is received.

Since the receiver amplifier has high gain, the possibility of false output from the comparator due to the presence of low level interference may exist during the activation phase of the transmitted signal. This possibility is avoided through use of a 74121 one shot which inhibits the receiver comparator output during this period. This one shot is enabled by the transmitter enabling pulse from the CPU through the 6820 at line PB7. The output of the 74121 is set at about 10 usec. This time period is of sufficient length to prevent false firing of the comparator (set as a threshold detector).

A CD4052 analog switch is used for selection of either one of the two transmitters for activation. The transmitter enabling pulse from line PB7 of the 6820 (1) is input to the 4052 where it is multiplexed
to output at either $X_0$ (pin 12) or $X_1$ (pin 14). Two transistors (2N222) at the output are used to convert the logic levels from the analog switch to a 15 V pulse to activate the ultrasonic transmitting circuit (pinger). S1 (pin 9) and S0 (pin 10) of the 4052 are the multiplexer select lines. S1 is grounded (Logic Level "0") since only two of the outputs are used and SO is connected to the mode switch.

A two-pole three position slide switch is used as a mode selector. In the first two positions a ground level is sensed by line PB4 of the 6820 and notifies the CPU to send out approximately a 2 Khz pulse test signal to either one of the transducer enabling inputs of the transmitting "pinger", depending on the position of the switch. This in turn will provide a continuous pulsed ultrasound output so that the operator can place the receiver transducer at a proper position. In position 3, the run mode, the CPU takes over and selection of the transmitter is controlled by the stored program.

Power Supply Circuits

Power for all clocks of the system is supplied by the TM515 power module. Fig. 43 shows the designed voltage regulator circuits to convert this power source into the required 5V, 12V, and 15V required by the system. The three circuits operate as follows:

Figure 43A produces +15V and +12V. A regulated voltage source provided by a 15V Zener diode and a pnp power transistor produces the -15V supply. A second similar voltage source using a npn transistor produces the +15V supply. The +15V supply is also used as the input to an LM 7812 +12V precision voltage regulator which produces the 12V supply. Capacitors are used to filter out any AC ripple.

Since the LED displays do not require a precise voltage source, a simple voltage dividing network, shown in Fig. 43B, is used to
FIGURE 43- Schematic of power supply circuits used in two transmitter ULVS
produce its 5V supply. Line voltage is stepped down to 25V through a transformer. A pnp power transistor and three resistors are used to produce the voltage divider which produces 5V at the output of Fig. 43B. In order to prevent the 100 mf capacitor from discharging back into the transformer, a diode is included at the input. Capacitors are used at the input and output to filter out any AC ripple.

Two +5V precision voltage regulators (LM 7805) and one -5V precision voltage regulator (LM 7905) are used in Fig. 43B to produce the 5V supplied. Line voltage is stepped down to 15V through a center tapped transformer. The center tap is grounded. Full wave rectification of the secondary voltage across the end terminals of the top portion of Fig. 43C is accomplished by tow diodes. A regulated voltage source, provided by an npn transistor and a 9V Zener diode with input and output capacitors for filtering out ac ripple, is used as an input to the two 7805's. Half wave rectification of the secondary voltage across the end terminals of the lower portion of Fig. 43C is accomplished by one reverse-biased diode to allow only negative voltages to pass. This is used as the input to 7905, which produces the -5V supply. Transistors Q₁ through Q₂ are power transistors supplied by the TM 515 power module. All resistors are 1 watt.
SOFTWARE IMPLEMENTATION

The operation of the Ultrasonic Plethysmograph is controlled by the 8080 microprocessor and the program implemented in the 8080 provides the process for determining limb cross-sectional area. To fully understand the operation of this device it is necessary to understand the software implementation. A flow graph of the program is shown in Fig. 44.

The program counter within the 8080 microprocessor chip is initialized through a SPST pushbutton switch located on the front panel. Automatic power-on-reset of the program counter is provided through an R-C charging network. The program begins with initialization of the 6820 PIA. The stack pointer is then set up followed by the choice of operating mode. In the testing mode a 2 KHz pulse repetition frequency (prf) is used to excite one of the transducers based on the position of the selector switch. This feature enables one to observe the received signals on the oscilloscope screen and adjust the transducer locations for optimum results. Once the optimum transducer sites have been located, the selector switch is moved to position 3, run mode, indicating that limb area computations may now be carried out. It begins by resetting the binary counters upon activation of transducer 1. The program then calls subroutine "NOTYET" shown in Fig. 45. This subroutine takes the binary count, which is the time required for the ultrasonic pulse to traverse from transmitter to receiver, and converts it into a corresponding chord length, \(d_1\). This information is stored in the RAM. In a similar manner the second chord length data, \(d_2\), is obtained and stored. The limb cross-sectional area is computed and
Delay

Enable either one of the TX transducers

Initializesation of 6820 PIA

Testing Mode

Reset Counter

Enable Tx Transducer 1

Call subroutine "No Yet"

Store $d_1$

Reset Counter

Enable Tx Transducer 2

Call "No Yet"

Store $d_2$

Compute limb cross-section area based on $d_1$ & $d_2$

Display Result

Delay

A

FIGURE 44. Flow Graph of Software Implementation
Take binary count data from counter

Convert into floating point format

Normalize

Return

Figure 45. Subroutine "NOTYET"
displayed on the front panel LED readout. After a delay (firmware adjustable, normally set at 1 sec), the program returns to the testing mode and a second sequence of events begins, unless the selector switch is moved to positions 1 or 2.

A complete listing of software is included in the following pages.
SOFTWARE PROGRAM LISTING

; ************************************************************
; ULTRASONIC LOWER LIMB AREA COMPUTATION.
; ************************************************************

; THIS IS A PROGRAM TO COMPUTE AREA OF
; A SEGMENT OF THE LOWER LIMB UNDER MEASUREMENT.
; COMPUTATIONS ARE DONE BY UTILIZING FLOATING
; POINT ROUTINES WHICH ARE ADOPTED AND
; MODIFIED FROM THE INITIAL VERSION OF IMSAI
; 8K BASIC SOURCE LISTING. THESE ROUTINES ARE
; LISTED FOR REFERENCE.

; PARAMETERS ARE DEFINED AS FOLLOWS:
; D1= DISTANCE BETWEEN 1ST TRANSMITTING TRANSDUCER
; AND THE RECEIVING TRANSDUCER.
; D2= DISTANCE BETWEEN 2ND TRANSMITTING TRANSDUCER
; AND THE RECEIVING TRANSDUCER.
; D= DISTANCE BETWEEN TWO TRANSMITTING TRANSDUCERS.
; WHICH IS PRESETED AS 2.5 (CM).
; PROGRAM IS STORED IN TWO 2708 EPROMS AND
; STRAT AT LOCATION 0.
; GENERATED AND TEMPERARY DATAS ARE STORED IN
; TWO 4 BY 256 RAM WHICH ARE LOCATED AT 800H.
; FLOATING POINT DATAS ARE STORED IN 4 CONSECUITIVE
; BYTES WITH THE 1ST BIT OF THE 1ST BYTE
; BE THE SIGN OF THE MANTISA AND 2ND BIT OF THE 1ST
; BYTE BE THE SIGN OF EXPONENT. THE REST
; OF THE 1ST BYTE IS EXPONENT AND THE FOLLOWED
; 3 BYTES ARE MANTISA.
;
; ************************************************************
; ORG 0
;
; ************************************************************
; SET THE STACK POINTER AT 43000H(980H).
; LOCATIONS 800H TO 97FH ARE SAVED TO
; STORE GENERATED AND TEMPERARY DATAS.
; LXI SP,43000
;
; ************************************************************
; INITIALIZE PIA( MOTOROLA 6820).
; PIA(1) CHANNEL A IS SET AS INPUT.
; PIA(1) FIRST 2 BITS OF CHANNEL B
; IS SET AS OUTPUT OTHERS AS INPUT.
INPUT ARE FROM BINARY COUNTER, OUT.
PUT ARE TO THE CONTROLLING LOGIC.
PIA(2) CHANNEL A AND B ARE SET AS OUTPUT ONLY.
REFER TO CHAPTER 4 FOR DETAILS.

XRA A ;CLEAR A.
OUT 1 ;ACCESS DATA DIRECTION

0003 AF XRA A ;CLEAR A.
0004 D301 OUT 1 ;ACCESS DATA DIRECTION
0006 D303 OUT 3 ;REGISTERS.
0008 D305 OUT 5
000A D307 OUT 7
000C D300 OUT 0 ;SET AS INPUT.
000E 3E00 MVI A,3000
0010 D302 OUT 2
0012 3E00 MVI A,3770
0014 D304 OUT 4 ;SET AS OUTPUT.
0016 D306 OUT 6
0018 3E34 MVI A,64Q
001A D301 OUT 1 ;ACCESS DATA REGISTERS.
001C D301 OUT 1
001E D303 OUT 3
0020 D305 OUT 5
0022 D307 OUT 7

**************************************************************
IN THE FOLLOWING THE STATUS OF THE MODE SELECTION SWITCH IS DETECTED.
IF THE MODE IS SELECTED AS TESTING, A 2KHZ PULSE IS SENT TO EITHER ONE OF THE TRANSMITTING TRANSDUCERS. OTHERWISE COMPUTATION SEQUENCE IS RESUMED.

0024 DB02 SNP IN 2 ;CHECK TESTING?
0026 E010 ARI 0200
0028 C24000 JNZ FREE ;JUMP IF NOT TESTING.
002B 3E80 MVI A,200Q ;OTHERWISE TURN ON PULSE.
002D D302 OUT 2
002F 3E00 MVI A,0 ;TURN OFF PULSE.
0031 D302 ——— OUT 2
0033 2100Q0 LXI H,0
0036 7D DL MOV A,L ;DELAY FOR 1/2 MSEC.
0037 23 INX H
0038 FE22 CPI 42Q
003A C23600 JNZ DL
003D C32400 JMP SNP

**************************************************************
START COMPUTATION SEQUENCE.
ROUTINES ARE SPECIFIED AS FOLLOWING,

123
; RST6 = STORE (A) INTO <H,L>
; RST5 = RESTORE <H,L> INTO (A)
; FACC = FLOATING POINT ACCUMULATOR.
; FMUL = FLOATING POINT MULTIPLICATION.
; FADD = FLOATING POINT ADDITION.
; FSUB = FLOATING POINT SUBTRACTION.
; FOUT = CONVERT FLOATING POINT NUMBERS INTO BCD.
; WHERE (A) IS CONTENTS OF A REGISTER.
; <H,L> IS LOCATION DEFINED BY REGISTER H AND L.

FREE MVI A,740 ; CLEAR COUNTER.
OUT 3
MVI A,640
OUT 3
MVI A,200Q ; SEND PULSE TO OUT 2
MVI A,640 ; ULTRASONIC PINGER.

CALL NOTYET ; GO CONVERTING ROUTINE.
LXI H,D1 ; STORE 1ST CHORD.
CALL RST6
MVI A,740 ; CLEAR COUNTER.
OUT 3
MVI A,640
OUT 3
MVI A,300Q ; SEND 2ND PULSE.
OUT 2
XRA A
OUT 2
MVI A,640
OUT 3
MVI A,300Q
OUT 2
XRA A

CALL NOTYET
LXI H,D2 ; STORE 2ND CHORD.
CALL RST6
LXI H,D1 ; RESTORE D1.
CALL RST5
LXI H,FACC
CALL FMUL ; GET D1 SQUARE.
LXI H,D1
CALL RST6 ; STORE D1 SQUARE.
LXI H,D2
CALL RST5
LXI H,FACC
CALL FMUL ; GET D2 SQUARE.
LXI H,D2
CALL RST6 ; STORE D2 SQUARE.
LXI H,D1
CALL FADD ; ADD D1^2 AND D2^2.
LXI H,DC
CALL FSUB ; SUBTRACT BY D^2.
LXI H,VA
CALL RST6 ; STORE IT.
LXI H,FACC
THIS SUBROUTINE DISPLAY THE BCD RESULTS
FROM FOUT ROUTINE ONTO FRONT PANEL LED DISPLAY.
; THE RESULTS FROM FOUT IS ASSUMED TO BE LESS THAN
; 200 CM SQUARE AND GREATER THAN 20 CM SQUARE.

0136 = DISP EQU $0136 3E34 MVI A,640
0138 F24201 JP REPT IF NOT SKIP IT.
013A F25E01 JP SKIP SKIP IF NOT.
013C 111208 LXX D,OUTSTR SET DISPLAY BUFFER.
013E 214508 LXX H,STRIN ;LOCATE BCD RESULT.
0142 7E REPT MOV A,M
0144 7E MOV A,M
0146 7E MOV A,M
0148 0D DCR C LESS ONE DIGIT.
014A 13 INCX D INCREMENT BUFFER.
014C C24201 JNZ REPT GO REPEAT IF MORE DIGIT.
014E 211208 LXX H,OUTSTR ;LOCATE BUFFER.
0152 7E MOV A,M
0154 7E MOV A,M
0156 7E MOV A,M
0158 7E MOV A,M
015A 07 RLC ;ROTATE TO LEFT.
015C 07 RLC
015E 07 RLC
0160 07 RLC
0162 07 RLC
0164 E6FO ANI OFOH ;STRIP TO 4 BITS.
0166 86 ADD N ;MERGE WITH NEXT BCD.
0168 D306 OUT 6 ;DISPLAY IT(2 DIGITS).
016A 23 INX H
016C 07 RLC
016E 07 RLC
0170 E6FO ANI OFOH
0172 23 INX H
0174 86 ADD N ;MERGE WITH LAST BCD.
0176 D304 OUT 4 ;DISPLAY AT LAST 2 DIGITS.
0178 210000 LXX H,O DELAY FOR 1 SEC.
017A 7E DL1 MOV A,H
017C C27B01 JNZ DL1
017E C9 RET ;RETURN.
; FLOATING POINT MULTIPLICATION SUBROUTINE.
; FLOATING POINT MULTIPLY THE NUMBER AT (H,L) TO
; THE FACC.

FMUL  EQU $-$

0180  CD6303     CALL  FTEST
0183  CB         RZ
0184  23         INX  H
0185  7E         MOV  A,M
0186  2B         DCX  H
0187  B7         ORA  A
0188  CA8803     JZ   RST5
0189  113108     FMUL1 LXI  D,FACC
018E  1A         LDAX  D
018F  CD7103     CALL  FEXP
0192  47         MOV  B,A
0193  7E         MOV  A,M
0194  CD7103     CALL  FEXP
0197  80         ADD  B
0198  CDD703     CALL  FOVUN
019B  E67F       ANI  127
019D  47         MOV  B,A
019E  1A         LDAX  D
019F  AE         XRA  M
01A0  E680       ANI  128
01A2  80         ORA  B
01A3  12         STAX  D
01A4  113E08     LXI  D,FTEMP+9
01A7  0603       MVI  B,3
01A9  23         INX  H
01AA  CD7803     CALL  COPYH
01AD  213508     LXI  H,FTEMP
01B0  0606       MVI  B,6
01B2  CDE703     CALL  ZEROM
01B5  113208     LXI  D,FACC+1
01BB  0603       MVI  B,3
01BA  1A         FMUL5  LDAX  D
01BB  77         MOV  M,A
01BC  AF         XRA  A
01BD  12         STAX  D
01BE  13         INX  D
01BF  23         INX  H
01C0  05         DCR  B
01C1  C2BA01     JNZ  FMUL5
01C4  0618       MVI  C,2A

01C6  0603       FMUL6  MVI  B,3
01CB  213E08     LXI  H,FTEMP+9
01CC  7E         FMUL7  MOV  A,M
01CD  1F         RAR
01CE  77         MOV  M,A

127
01CF 23  INX  H
01D0 05  DCR  B
01D1 C2CC01  JNZ  FMUL7
01D4 02E201  JNC  FMUL8
01D7 113710  LXI  D,FTEMP+2
01DA 213D08  LXI  H,FTEMP+8
01DD 0606  MVI  B,6
01DF CD7D03  CALL  FADDT
01E2 0606  FMUL8  MVI  B,6
01E4 213D08  LXI  H,FTEMP+8
01E7 AF  XRA  A
01EB 7E  FNUL9  MOV  A,M
01E9 17  RAL
01EA 77  MOV  M,A
01EB 2B  DCX  H
01EC 05  DCR  B
01ED C2E801  JNZ  FMUL9
01FO 0D  DCR  C
01F1 C2C601  JNZ  FMUL6
01F4 C39003  JMP  FNORM

;********************************************************************
; FLOATING POINT OUTPUT ROUTINE.
;
; THIS SUBROUTINE CONVERTS A NUMBERS IN THE FLOATING
; POINT ACCUMULATOR TO A BCD STRING SUITABLE FOR DISPLAY.

01F7 =
01F7 113408  LXI  D,FACC+3
01FA 1A  LDAX  D
01FB F607  ORI  7
01FD 12  STAX  D
01FE CD6303  CALL  FTEST
0201 3620  MVI  M,'0'
0203 E20802  JP  FOUT0
0206 362D  MVI  M,'1'
0208 23  FOUTO  INX  H
0209 C21202  JNZ  FOUT2
020C 3630  MVI  M,'2'
020E 23  INX  H
020F 3620  FOUT1  MVI  M,'3'
0211 C9  RET
0212 3A1108  FOUT2  LDA  FACC
0215 CD7103  CALL  FEXP
0218 C21D02  JNZ  FOUTV
021B 3E80  MVI  A,128
021D E680  FOUTV  ANI  128
021F 320908  STA  DEXP
0222 E5  PUSH  H
0223 3A3108  FOUT3  LDA  FACC
0226 CD7103  CALL  FEXP
0229 FE01  CPI  1
022B F24402  JP  FOUT6

128
022E 210908 FOUT4 LXI D,DEXP
0231 34 INR M
0232 217C04 LXI H,TEN
0235 F23E02 JP FOUT5
0238 CD8001 CALL FHUL
023B C32302 JMP FOUT3
023E CDEF03 FOUT5 CALL FDIV
0241 C32302 JMP FOUT3
0244 FE05 FOUT6 CPI 5
0246 F22E02 JP FOUT4
0249 213508 LXI H,FTEMP
024C CDCF03 CALL RST6
024F 3A3108 LDA FACC
0252 CD7103 CALL FEXP
0255 0E06 NVI C,6
0257 CD8E02 CALL FOUTB
025A FE0A CPI 10
025C FA6802 JH FOUTU
025F 213508 LXI H,FTEMP
0262 CD8803 CALL RST5
0265 C32E02 JMP FOUT4
0268 CD9C02 FOUTU CALL FOUT9
026B AF FOUT7 XRA A
026C 323108 STA FACC
026F CD9202 CALL FOUT8
0272 213508 LXI H,FTEMP
0275 CDCF03 CALL RST6
0278 CD9202 CALL FOUT8
027B CD9202 CALL FOUT8
027E 113408 LXI D,FACC+3
0281 213808 LXI H,FTEMP+3
0284 0604 NVI B,4
0286 CD7D03 CALL FADDT
0289 CD9C02 CALL FOUT9
028C CD8902 JNZ FOUT7
028F C3C502 JMP FOUTH
0292 213408 FOUT8 LXI H,FACC+3
0295 54 MOV D,H
0296 5B MOV E,L
0297 0604 NVI B,4
0299 C37D03 JMP FADDT
029C F600 FOUT9 ORI 0
029E E1 POP H
029F E3 XTHL
02A0 77 MOV M,A
02A1 23 INX H
02A2 79 MOV A,C
02A3 FE06 CPI 6
02A5 C2AB02 JNZ FOUTA
02A8 362E NVI H,'-'
02AA 23 INX H
02AB E3 FOUTA ITHL

129
02AC 0D  DCR  C
02AD E9  PCHL
02AE 5F  FOUTB  MOV  E,A
02AF AF  XRA  A
02B0 323108  STA  FACC
02B3 213408  FOUTC  LXI  H,FACC+3
02B6 0604  CVI  B,A
02B8 7E  FOUTD  MOV  A,M
02B9 17  RAL
02BA 77  MOV  M,A
02BB 2B  DCX  H
02BC 05  DCR  B
02BD C2802  JNZ  FOUTD
02C0 1D  DCR  E
02C1 C2802  JNZ  FOUTC
02C4 C9  RET
02C5 E1  FOUTH  POP  H
02C6 3645  MVI  M,F,"E"
02C8 23  INX  H
02C9 3A0908  LDA  DEXP
02CC 3628  MVI  M,F,"E"
02CE 57  MOV  D,A
02CF B7  ORA  A
02D0 F2DC02  JP  FOUTI
02D3 3620  MVI  H,F,"E"
02D5 E67F  ANI  127
02D7 2F  CMA
02D8 3C  INR  A
02D9 57  MOV  D,A
02DA 2F  CMA
02DB 3C  INR  A
02DC 23  FOUTI  INX  H
02DD E5  PUSH  H
02DE 1EFF  MVI  E,OFFH
02E0 1C  FOUTJ  INR  E
02E1 D60A  SUI  10
02E3 F2E002  JP  FOUTJ
02E6 C60A  ADI  10
02EB 47  MOV  B,A
02E9 7B  MOV  A,E
02EA CD9C02  CALL  FOUT9
02ED 7B  MOV  A,3
02EE CD9C02  CALL  FOUT9
02F1 E1  POP  H
02F2 3620  MVI  H,F,"E"
02F4 7A  MOV  A,D
02F5 B7  ORA  A
02F6 F2FF02  JP  FOUTK
02F9 FEFE  CPI  OFEH ;-2
02FB D8  RC
02FC C30203  JMP  FOUTL

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02FF FE06  FOUTK  CPI    6
0301 D0  RNC
0302 4F  FOUTL  MOV  C,A
0303 0605  MVI  B,5
0305 3620  FOUTH  MVI  M,'0'
0307 2B  DCX  H
0308 05  DCR  B
0309 C20503  JNZ  FOUTH
030C EB  XCHG
030D 2B  MOV  A,E
030E D605  SUI  5
0310 6F  MOV  L,A
0311 7A  MOV  A,D
0312 DE00  SBI  0
0314 67  MOV  H,A
0315 79  MOV  A,C
0316 B7  ORA  A
0317 CA2803  JZ  FOUTO
031A FA3D03  JK  FOUTR
031D 46  FOUTH  MOV  B,N
031E 23  INX  H
031F 7E  MOV  A,M
0320 70  MOV  H,B
0321 2B  DCX  H
0322 77  MOV  H,A
0323 23  INX  H
0324 0D  DCR  C
0325 C21D03  JNZ  FOUTN
0328 EB  FOUTQ  XCHB
0329 7E  FOUTP  MOV  A,M
032A FE30  CPI  '{0'}
032C C33503  JMP  FOUTO
032F 3620  MVI  M,'0'
0331 2B  DCX  H
0332 C32903  JMP  FOUTP
0335 FE2E  FOUTQ  CPI    '{0'}
0337 23  INX  H
0338 C0  RNZ
0339 2B  DCX  H
033A 3630  MVI  M,'0'
033C C9  RET
033D FEFF  FOU TR  CPI  255
033F C24B03  JNZ  FOUTS
0342 2B  DCX  H
0343 7E  MOV  A,M
0344 362E  MVI  M,'0'
0346 23  INX  H
0347 77  MOV  M,A
0348 C32803  JMP  FOUTO
034B 2B  FOUTS  DCX  H
034C 7E  MOV  A,M
034D 3630  MVI  M,'0'
034F 23  INX  H
0350 77  MOV  M,A
0351 62  MOV  H,D
0352 6B  MOV  L,E
0353 0606  MVI  B,6
0355 2B  FOUTT  DCX  H
0356 7E  MOV  A,N
0357 23  INX  H
0358 77  MOV  N,A
0359 2B  DCX  H
035A 05  DCR  B
035B C25503  JNZ  FOUTT
035E 362E  MVI  M,‘.’
0360 C32803  JMP  FOUTO

; TEST THE SIGN OF THE NUMBER IN THE FACC.

0363 = FTEST EQU $ 
0363 3A3208  LDA  FACC+1
0366 B7  ORA  A
0367 C8  RZ
0368 3A3108  LDA  FACC
0369 F67F  ORI  127
036D 3A3108  LDA  FACC
0370 C9  RET

; EXPAND EXPONENT INTO 8 BINARY BITS.

0371 = FEXP EQU $ 
0371 E67F  ANI  127
0373 C640  ADI  64
0375 EE40  XRI  64
0377 C9  RET

; MOVE THE STRING FROM (H,L) TO (D,E) COUNT IN B.

0378 = COPYH EQU $ 
0378 EB  XCHG
0379 CDC603  CALL COPYD
037C C9  RET

; ADD TWO MULTIPRECISION NUMBERS (D,E) & (H,L).

037D = FADT EQU $ 
037D AF  XRA  A
037E 1A  FAD1  LDAX  D
037F 8E  ADC  M
0380 12  STAX  D
0381 1B  DCX  D
0382 2B  DCX  H

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```
0383 05          DCR  B
0384 C27E03       JNZ  FAD1
0387 C9          RET

;****************************************************************************
; LOAD THE FLOATING POINT ACCUMULATOR WITH THE 4 BYTES
; AT (H,L).
0388 =
RST5  EQU  $8
0388 113108       LXI  D,FACC
038B 0604         MVI  B,4
038D C37803       JMP  COPYH

;****************************************************************************
; NORMALIZE THE FLOATING ACCUMULATOR. THAT IS,
; THE FIRST BIT MUST BE SIGNIFICANT.
0390 =
FNORM  EQU  $8
0390 213408       LXI  H,FACC+3
0393 7E           MOV  A7,M
0394 2B           DCX  H
0395 B6           ORA  M
0396 2B           DCX  H
0397 B6           ORA  M
0398 C27E03       JNZ  FNRM1
039B 2B           DCX  H
039C 77           MOV  M4,A
039D C9           RET
039E 7E           FNRM1  MOV  A7,M
039F B7           ORA  A
03A0 FA6303       JM  FTEST
03A3 23           INX  H
03A4 23           INX  H
03A5 0603         MVI  B3,3
03A7 AF           XRA  A
03A8 7E           FNRM2  MOV  A7,M
03A9 17           RAL
03AA 77           MOV  M4,A
03AB 2B           DCX  H
03AC 05           DCR  B
03AD C2A803       JNZ  FNRM2
03B0 7E           MOV  A7,M
03B1 CD7103       CALL  FEXP
03B4 3D           DCR  A
03B5 FE80         CPI  128
03B7 CA0000       JZ  OVERR
03BA E67F         ANI  127
03BC 47           MOV  B3,A
03BD 7E           MOV  A7,M
03BE E680         ANI  128
03C0 30           ORA  B
03C1 77           MOV  M4,A
03C2 23           INX  H
```
; MOVE THE STRING FROM (D,E) TO (H,L) COUNT IN B.

JMP FNRM1

; STORE THE FLOATING POINT ACCUMULATOR AT (H,L)

; TEST EXPONENT FOR OVERFLOW OR UNDERFLOW.

; MOVES A STRING OF BINARY ZEROs,COUNT IN B.

; FLOATING POINT DIVISION SUBROUTINE.

; FLOATING POINT DIVIDE THE NUMBER AT (H,L) INTO THE FACC.
DCX H
ORA A
JZ OVERR
MOV A, M
CALL FEXP
MOV B, A
LXI D, FACC
LDAX D
CALL FEXP
SUB B
INR A
CALL FOVUN
FDIV3 LDAX D
MOV H, A
LXI H, FTEMP
ANI 128
ORA B
PUSH H
STAX D
INX D
LDAX B, 3
FDIV3
MOV M, A
XRA A
INX D
MOV B, 3
INX D
DCP. B
JNZ FDIV3
POP D
MOV B, 3
INX D
COPYD
MOV C, 24
FDIV5 LXI D, FTEMP + 3
FDIV5 LXI H, FTEMP + 7
FDIV5 LXI D, FTEMP + 3
FDIV5 LXI H, FTEMP + 7
FDIV6 BD, 4
FDIV6 BD, 4
FDIV6 BD, 4
STC
CMC
044F 0603  MVI  B,3
0451 213408  LXI  H,FACC+3
0454 7E  FDIU7  MOV  A,M
0455 17  RAL
0456 77  MOV  M,A
0457 28  DCX  H
0458 05  DCR  B
0459 C25404  JNZ  FDIU7
045C AF  XRA  A
045D 0604  MVI  B,4
045F 213808  LXI  H,FTEMP+3
0462 7E  FDIU8  MOV  A,M
0463 17  RAL
0464 77  MOV  M,A
0465 28  DCX  H
0466 05  DCR  B
0467 C26204  JNZ  FDIU8
046A 0B  DCR  C
046B C3404  JNZ  FDIU5
046E C39003  JMP  FNDN

;**********************************************************************
; SUBTRACT THE TWO MULTIPRESION NUMBERS (D,E) & (H,L)

0471 =  FSBT  EQU  $
0471 AF  XRA  A
0472 1A  FSB1  LDAX  D
0473 9E  SBB  H
0474 12  STAX  D
0475 18  DCX  D
0476 2B  DCX  H
0477 05  DCR  B
0478 C27204  JNZ  FSB1
047B C9  RET

;**********************************************************************
; FOLLOWING ARE CONSTANTS TO BE USED IN THE COMPUTATION
; SEQUENCES. ALL THE CONSTANTS ARE ARRANGED IN FLOATING
; POINT FORMAT.

047C 04  TEN  DB  04H ;INTEGER 10.
047D 0A  DB  0A0H
047E 00  DB  0
047F 00  DB  0
0480 03  DC  DB  03H ;SQUARE OF 2.5(CM).
0481 C9  DB  0CBH
0482 00  DB  00H
0483 00  DB  00H
0484 02  TWO  DB  02H ;INTEGER 2.
0485 80  DB  80H
0486 00  DB  0
0487 00  DB  0
0488 03  F4  DB  03H ;INTEGER 4.
0489 80  DB  80H
048A 90       DB  0
048B 00       DB  0
048C 01       F1 DB  1 ;INTEGER 1.
048D 80       DB  80H
048E 00       DB  00
048F 00       DB  00
0490 02       F2 DB  2 ;2.
0491 80       DB  80H
0492 00       DB  0
0493 00       DB  0
0494 02       PHI DB  2 ;PHI=3.1415926
0495 C9       DB  0C9H
0496 0F       DB  0FH
0497 D7       DB  0D7H
0498 7A       SPEED DB  7AH ;SPEED OF ULTRASOUND.
0499 8C       DB  8CH ;=0.15CH/USEC.
049A 44       DB  0A4H
049B 9C       DB  09CH

;*******************************************************************************
; FLOATING POINT ADDITION SUBROUTINE.
;*******************************************************************************
;
; FLOATING POINT ADD THE NUMBER AT (H,L) TO FACC
FADD EQU $    
049C 23       INX  N
049D 7E       MOV  A,H
049E B7       ORA  A
049F CA6303    JZ  FTEST
04A0 2B       BDX  H
04A3 CD6303    CALL FTEST
04A6 CA8803    JZ  RST5
04A9 113108    LXI  D,FACC
04AC 1A       LDAX  D
04AD CD7103    CALL FEXP
04B0 47       MOV  B,A
04B1 7E       MOV  A,H
04B2 CD7103    CALL FEXP
04B5 4F       MOV  C,A
04B6 90       SUB  B
04B7 CACC04    JZ  FADD4
04BA F28E04    JP   FADD3
04BD 2F       CMA
04BE 3C       INR  A
04BF FE18      FADD3 CPI  24
04C0 DACC04    JC  FADD4
04C1 78       MOV  A,B
04C5 91       SUB  C
04C6 F26303    JP   FTEST
04C9 C38803    JMP  RST5
04CC F5       FADD4 PUSH PSW
04CD C5       PUSH B
04CE 113508    LXI  D,FTEST
0401 0604  MVI  B,4
0403  CD7803 CALL  COPYH
0406  C1  POP  B
0407  F1  POP  PSW
0408  CAFFF04  JZ  FADD9
040B  213608  LXI  H,FTEMP+1
040E  F5  PUSH  PSW
040F  78  MOV  A,B
0410  91  SUB  C
0411  F2F104  JP  FADD6
0414  213108  LXI  H,FACC
0417  79  MOV  A,C
0418  E67F  ANI  127
041A  4F  MOV  C,A
041B  7E  MOV  A,M
041C  E680  ANI  128
041E  B1  ORA  C
041F  77  MOV  M,A
0420  23  INX  H
0421  F1  FADD6  POP  PSW
0422  4F  MOV  C,A
0423  0603  FADD7  MVI  B,3
0425  AF  XRA  A
0426  E5  PUSH  H
0427  CD7905  CALL  FSHT
042A  E1  POP  H
042B  0D  DCR  C
042C  C2F304  JNZ  FADD7
042E  FADD  EQU  5
0430  113108  LXI  D,FACC
0433  213508  LXI  H,FTEMP
0436  1A  LDAX  D
0437  AE  XRA  M
0438  FA3205  JM  FADDA
043B  113408  LXI  D,FACC+3
043E  213808  LXI  H,FTEMP+3
0441  0603  MVI  B,3
0442  C9D003  CALL  FADD8
0445  D26303  JNC  FTEST
0448  213108  LXI  H,FACC
044B  7E  MOV  A,M
044C  E680  ANI  128
044D  47  MOV  B,A
044E  7E  MOV  A,N
044F  CD7103  CALL  FEXP
0452  3C  INR  A
0453  E67F  ANI  127
0454  B0  ORA  B
0455  77  MOV  M,A
0456  23  INX  H

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FLOATING POINT SUBTRACTION SUBROUTINE.

FLOATING POINT SUBTRACT THE NUMBER AT (H,L) FROM THE FACC.

INCREMENTING SHIFT RIGHT.
; SUBROUTINE "NOTYET".
; THIS ROUTINE TAKES A BINARY NUMBER
; FROM THE COUNTER (THE COUNTER WHICH
; HAS THE TRAVERSE TIME INFORMATION)
; AND CONVERT IT INTO CORRESPONDING
; CHORD LENGTH.
; THE RESULT IS IN FLOATING POINT
; FORMAT AND IS NORMALIZED.

; ; NOTYET EQU $2
0582 DB02
0584 E620 ANI 0400 ; CHECK IF COUNTER READY?
0586 C28205 JNZ NOTYET ; GO BACK IF NOT.
0589 DB00 IN O ; OTHERWISE TAKE 1ST BYTE.
058B 5F MOV E,A ; STORE IT.
058C 07 RLC ; ROTATE IT.
058D 07 RLC
058E 07 RLC
058F 07 RLC
0590 E6FO ANI OFH ; STRIP INTO 4 BITS.
0592 323308 STA FACC+2 ; STORE INTO 3RD BYTE OF FACC.
0595 7B MOV A,E ; RESTORE 1ST BYTE.
0596 0F RRC ; ROTATE IT.
0597 0F RRC
0598 0F RRC
0599 0F RRC
059A E60F ANI OFH ; STRIP TO 4 BITS.
059C 5F MOV E,A ; STORE IN E.
059D DB02 IN 2 ; GET NEXT HIGHER BYTE.
059F 07 RLC ; ROTATE.
05A0 07 RLC
05A1 07 RLC
05A2 07 RLC
05A3 E6F0 ANI OF0H ; STRIP TO 4.
05A5 83 ADD E ; MERGE.
05A6 323208 STA FACC+1 ; STORE INTO FACC.
05A9 3E0C MVI A,0CH ; MOVE '12' INTO EXponent
05AB 323108 STA FACC ; OF FACC.
05AE 3E00 MVI A,0 ; CLEAR LAST BYTE OF
05B0 323408 STA FACC+3 ; FACC.
05B3 CD9003 CALL FNM; NORMALIZED IT.
05B6 219804 LXI H, SPEED ; MULTIPLIED COUNTS BY SPEED
05B9 CD8001 CALL FHUL ; TO GET CHORD LENGTH.
05BC C9 RET ; RETURN.
; FOLLOWING ARE DEFINED RAM AREAS.

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ORG 4000Q
REFERENCES:


