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NBSIR 75-756

ULTRASONIC INTERFEROMETER MANOMETER

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National Bureau of Standards
Department of Commerce
Washington, D.C. 20234

July 1975

Annual Report

Prepared for

CCG-Army/Navy
US Army Missile Command
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ABSTRACT

This report describes the design and construction of a 15 kPa - Ultrasonic Interferometer Manometer "ULTIMA II". The manometer consists of three mercury columns of 75 mm diameter with a maximum height difference of 110 mm. The column lengths are measured with ultrasonic interferometers in terms of the known wavelength of a 10 MHz sound wave in the mercury.

Construction of the manometer has been completed and the instrument is now being evaluated.

LIST OF FIGURES

INTRODUCTION

To measure pressure with a manometer requires the completion of four major steps:

1) The surfaces of the liquid columns must be located,

2) the location of the surfaces must be transferred to a scale,

3) the distance between the locations must be measured

and 4) the average temperature of the columns of liquid must be determined.

For accurate manometer measurements none of these tasks is trivial. In the ultrasonic interferometer manometer described in this report the first three steps are performed by ultrasonic interferometry; the fourth step is facilitated by the fact that the ultrasonic interferometer manometer is fully automatic. It can therefore be enclosed in a thermally lagged or thermostated enclosure, thus reducing temperature gradients and fluctuations.

The prototype described here, ULTIMA II, is designed for pressures up to 15 kPa, about 110 mmHg, with a resolution of about 5 Pa or better. Earlier experiments have shown that column length can be extended to one meter with a resolution of 10 Pa or better.

THE BASIC THEORY

Suppose a wave train of carrier frequency f traverses the length L of a liquid column several times undergoing multiple reflections at the top and bottom end faces. The p-th echo is finally picked up, amplified, and then demodulated in two phase sensitive detectors with continuous reference signals $r_1 = \cos wt$ and $r_2 = \sin wt$. The output signals from the detectors are

$$\begin{aligned} u_1 &= \cos(wt - 2p\beta L)\cos wt \\ u_2 &= \cos(wt - 2p\beta L)\sin wt \end{aligned} \tag{1}$$

with p the number of the echo , $\beta = 2\pi/\lambda$, and λ the wavelength in the liquid. We will assume that no phase change occurs in reflection and that the frequency f is constant enough not to change λ or effect phase changes in the amplifiers and detectors, which would interfere with the measurement. After some arithmetic we obtain from equ.(1)

$$\begin{aligned} u_1 &= \frac{1}{2}[\cos 2p\beta L + \cos(2wt - 2p\beta L)] \\ u_2 &= \frac{1}{2}[\sin 2p\beta L + \sin(2wt - 2p\beta L)] . \end{aligned} \tag{2}$$

The first terms in equ. (2) represent sinusoidal functions of sample length L. The second terms are high frequency signals to be suppressed with low pass filters. The first terms go through a full cycle whenever $2p\beta L$ changes by 2π. The change of L, the liquid column length, for a full cycle or fringe is

$$\Delta L = \lambda/2p . \tag{3}$$

The two electrical output signals of equ. (2) are our of phase by 90°. They contain the quadrature information necessary to discriminate between increasing or decreasing length of the sample. The vector defined by these two signals can be in one of four quadrants and the change of length per quadrant is

(4) $$\Delta L/\text{quadrant} = \lambda/8p.$$

This is illustrated by Fig. 1. Here the horizontal vector represents u_1 and the vertical vector represents u_2. The phase angle between them is 90°. These two component vectors determine the position of a third vector, which rotates left or right as the column moves. Note that for a given $\Delta L/\Delta t$, where t is time, the vector rotates faster the higher the echo number p is. Each time the vector moves into another quadrant a count signal is generated.

With $\beta = 2\pi/\lambda$ and $\lambda = c/f$ we have

(5) $$\Delta L/\text{count} = \frac{c}{8pf}\ .$$

The speed of sound c in mercury was previously determined as

$$c = 1449.57\ \text{m/s}$$

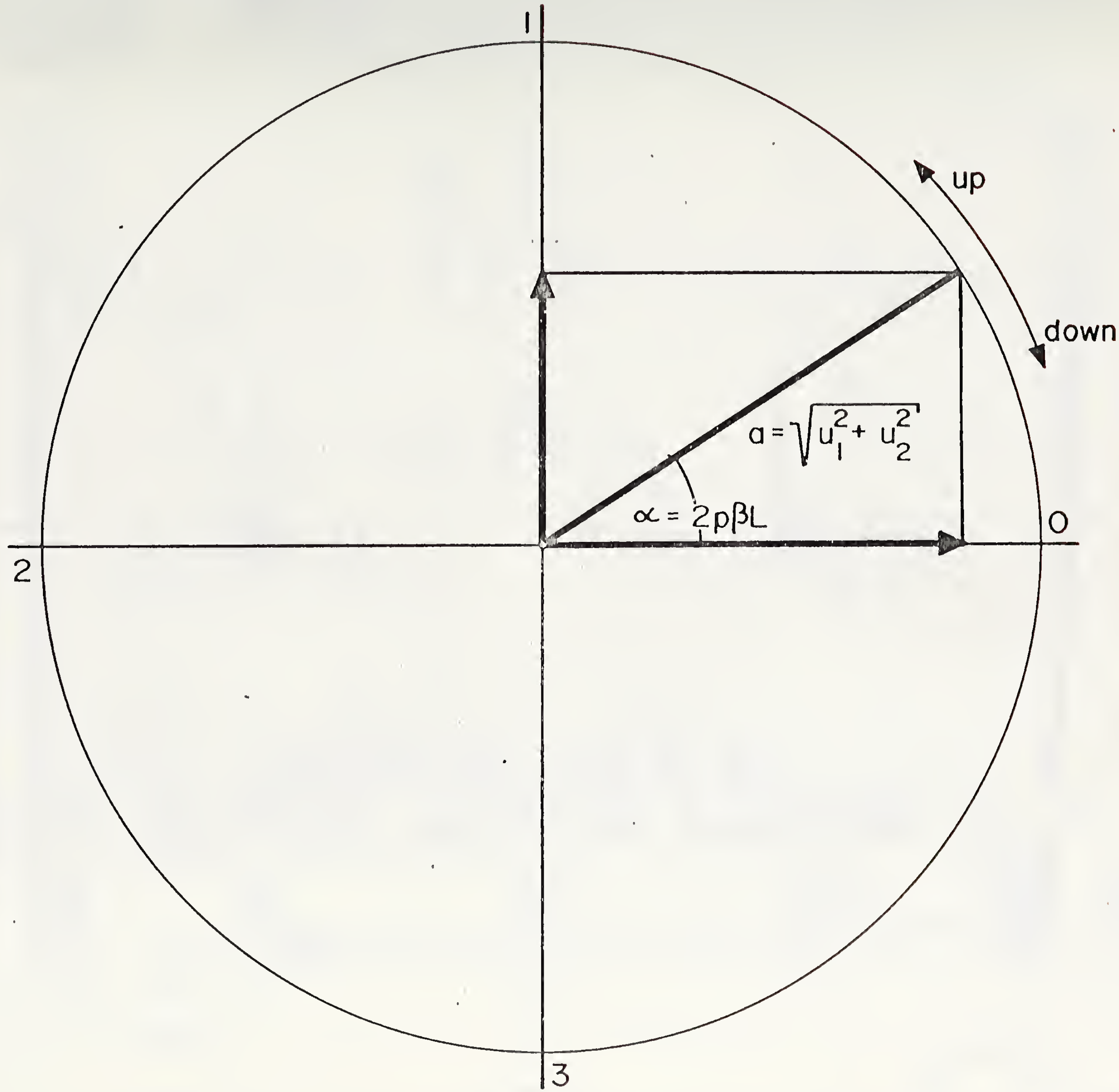
at 23°C with a precision of 0.03 m/s, an estimated systematic uncertainty of 0.05 m/s and a temperature coefficient of -3.2×10^{-4} °C^{-1}. With a frequency of 10.5 MHz the resolution per count using the second echo is

(6) $$\Delta L = 8.62\ \mu\text{m at } 23°\text{C}$$

This resolution can be improved by determining the instantaneous angle $\alpha = 2p\beta L$ from the component vectors u_1 and u_2. If α can be resolved to, for example, 10°, the resolution is improved to

(7) $$\Delta L = 0.96\ \mu\text{m}.$$

Examples of the achievable resolution are given in a later paragraph.


1
up
down
$a = \sqrt{u_1^2 + u_2^2}$
$\alpha = 2p\beta L$
0
2
3

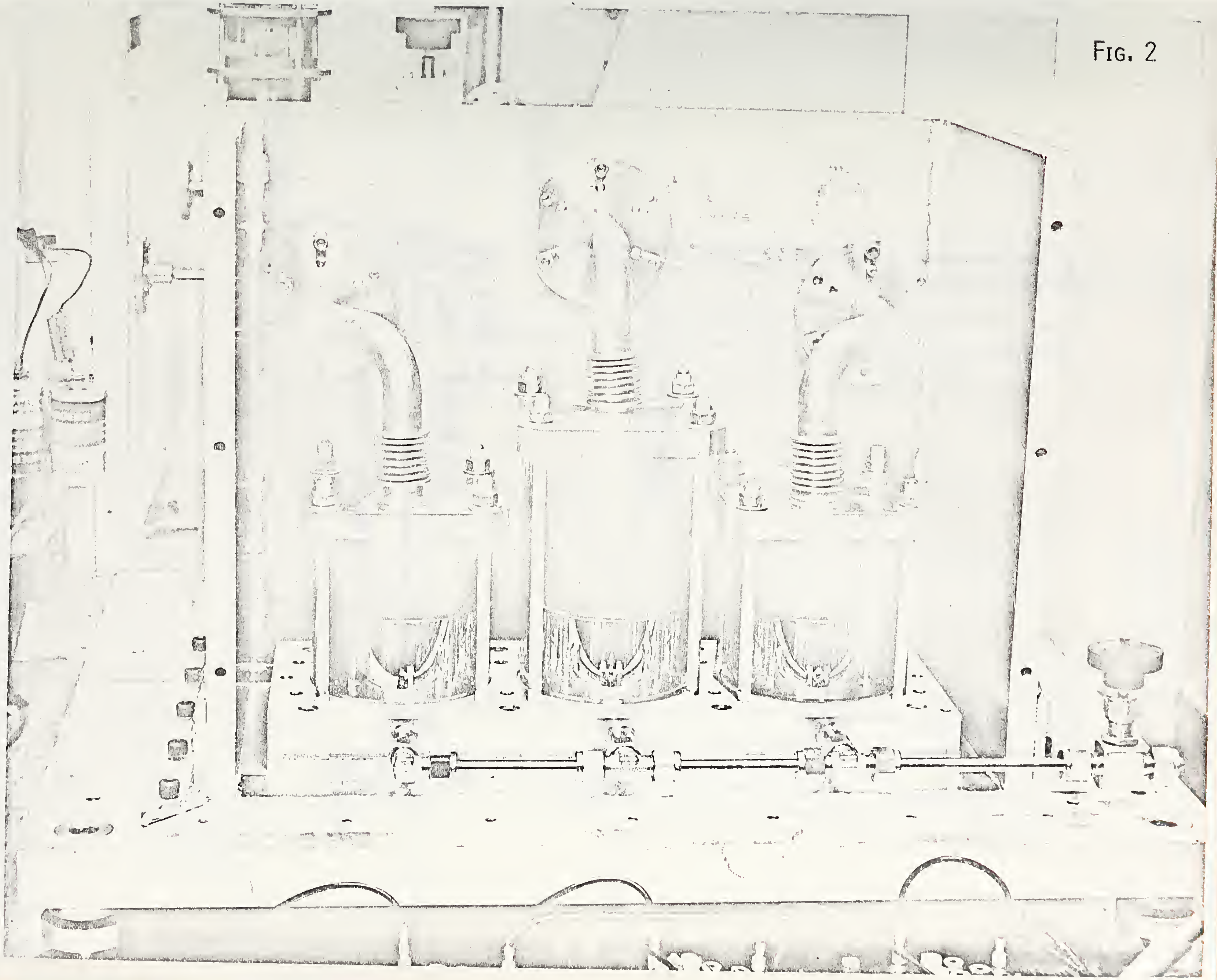


Fig. 2

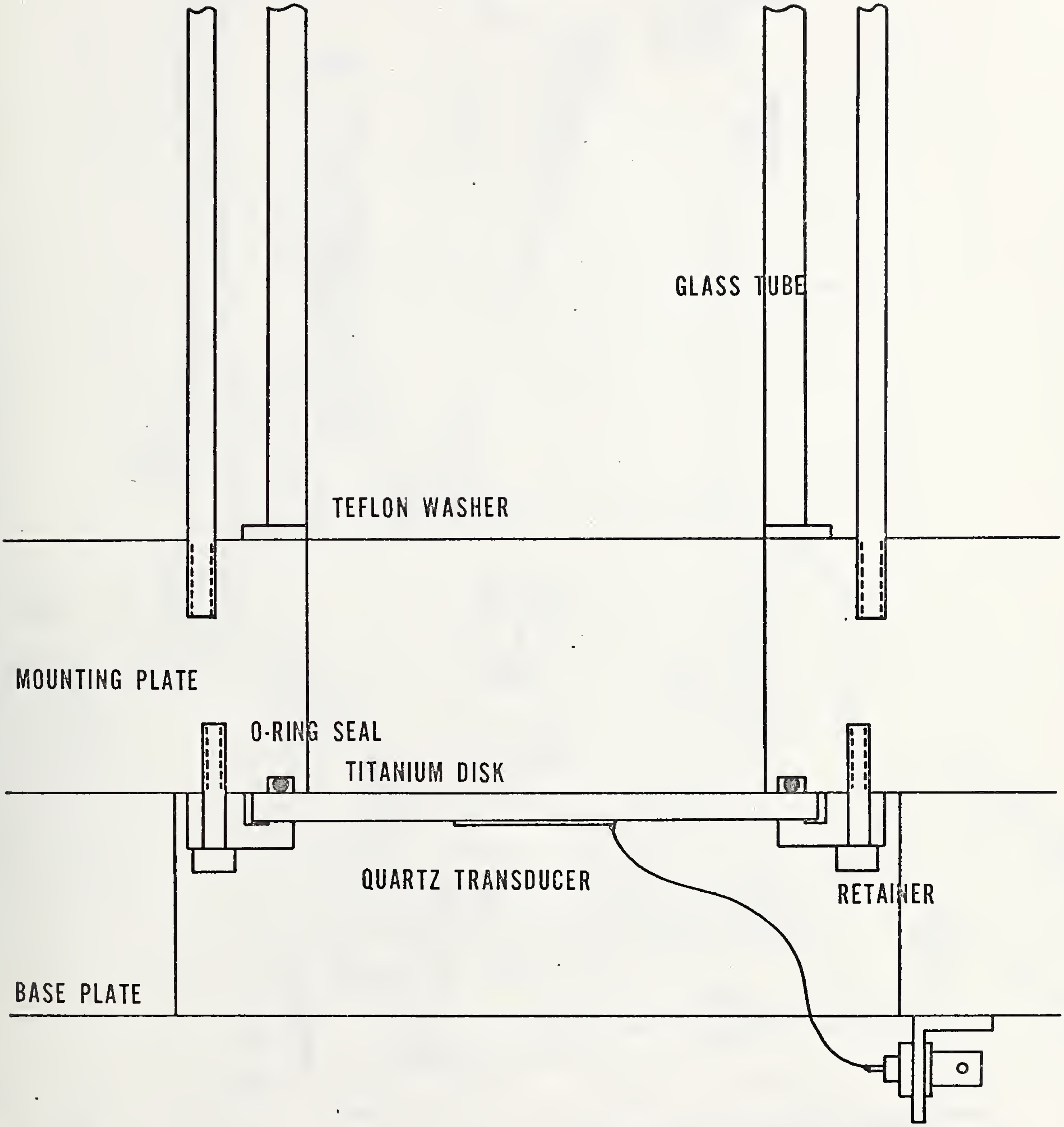
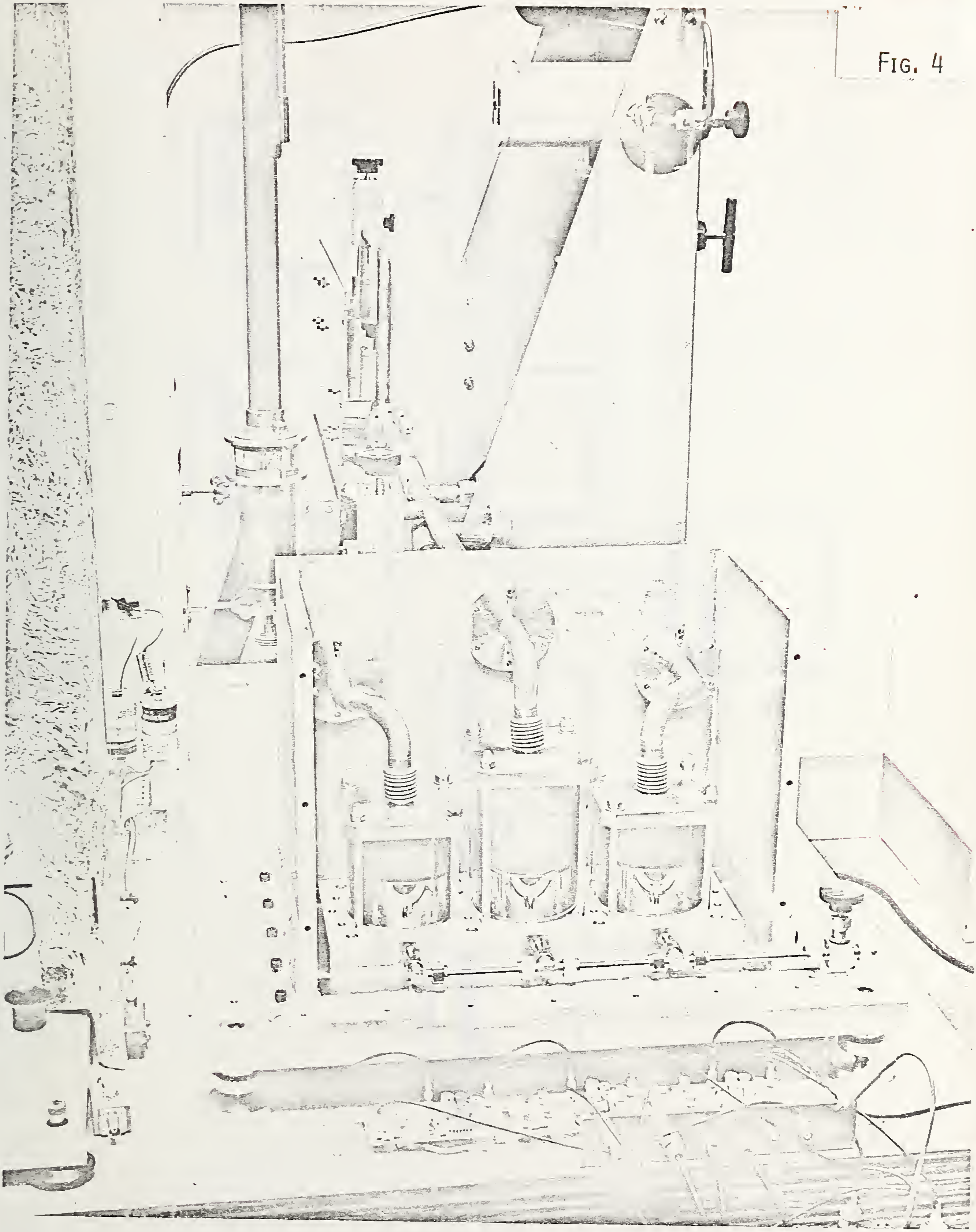
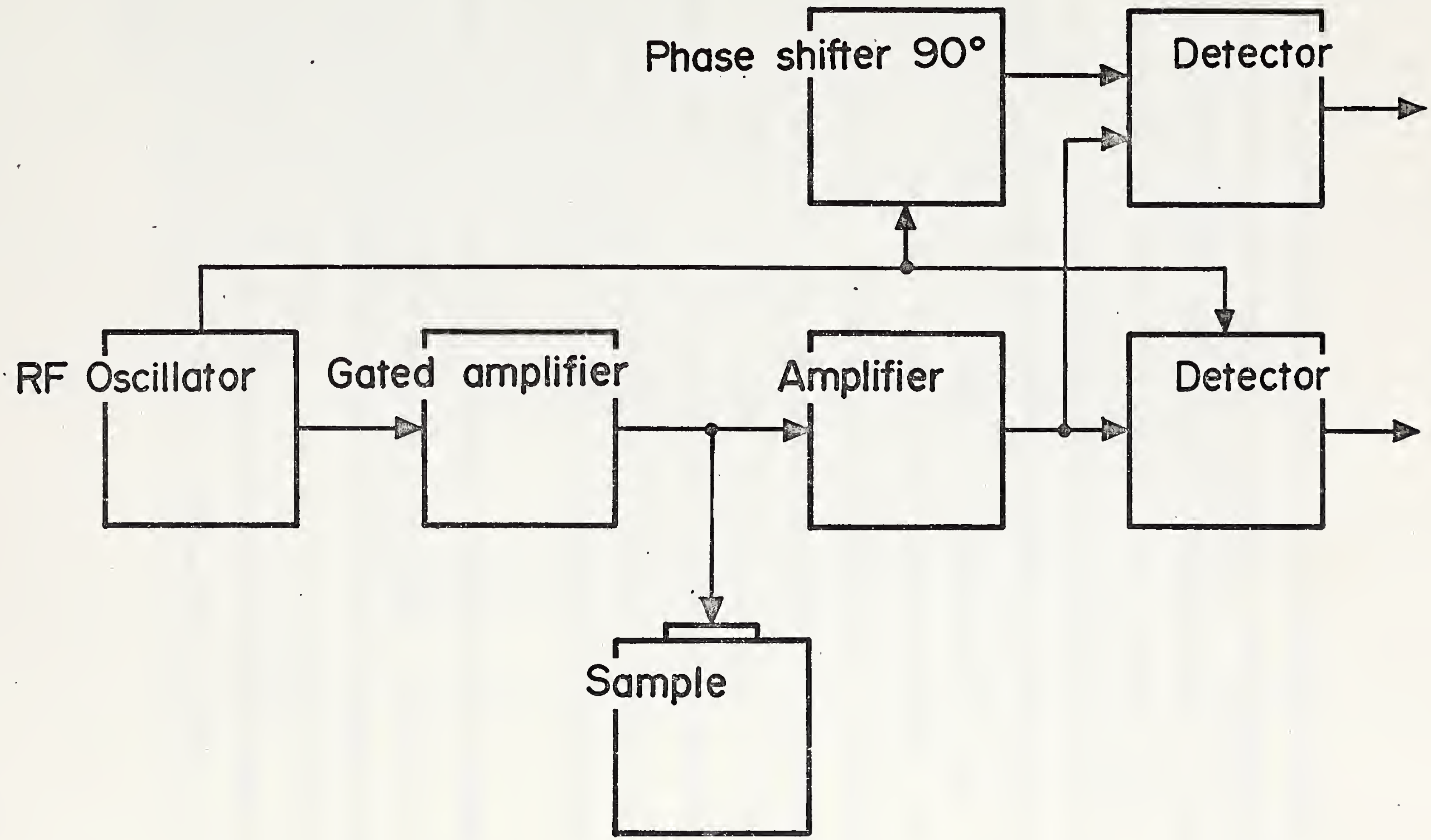

GLASS TUBE
TEFLON WASHER
MOUNTING PLATE
O-RING SEAL
TITANIUM DISK
QUARTZ TRANSDUCER
RETAINER
BASE PLATE

FIG. 3

FIG. 4





Phase shifter 90°
Detector
RF Oscillator
Gated amplifier
Amplifier
Detector
Sample

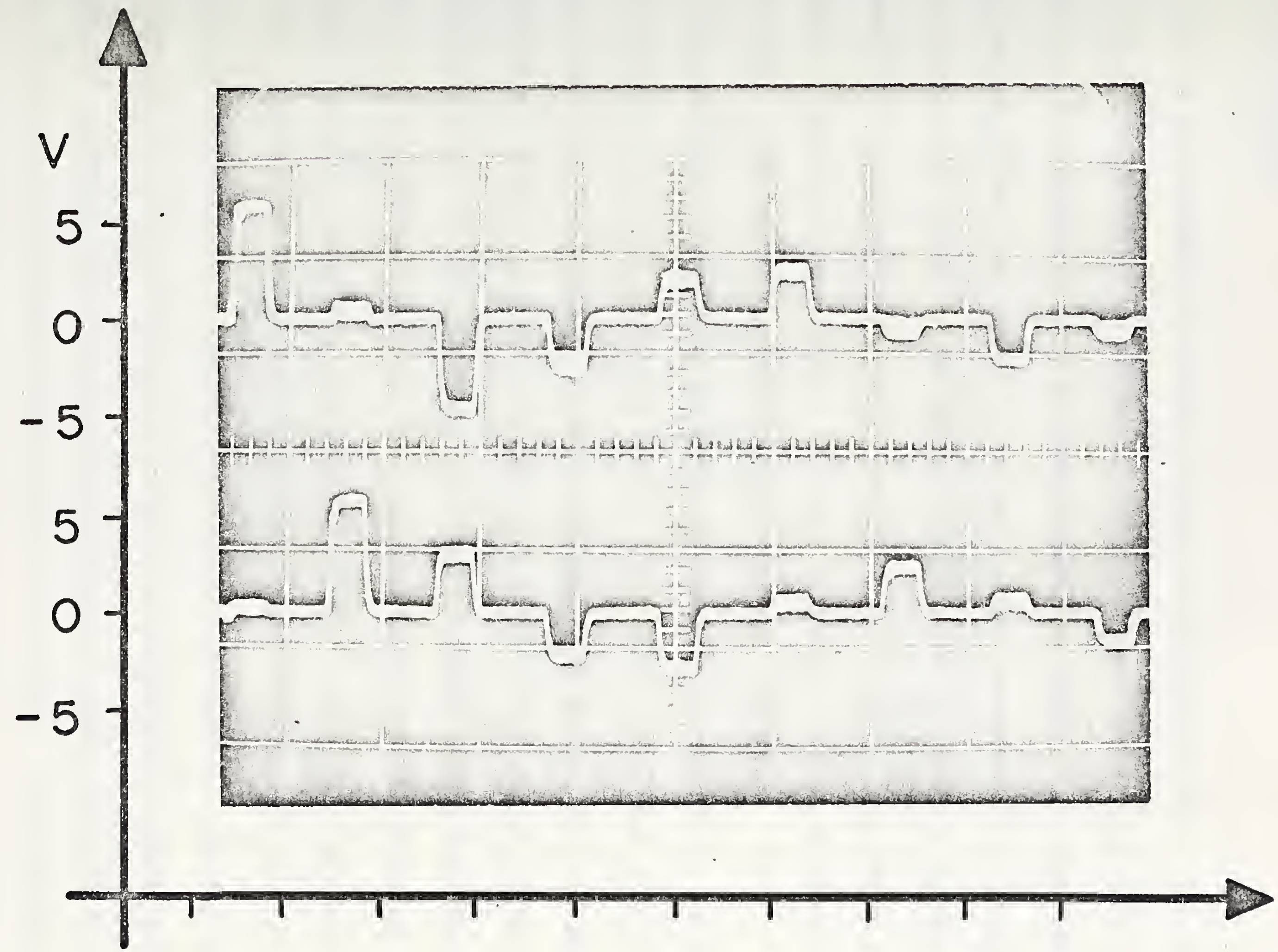
FIG. 5

THE MANOMETER

Fig. 2 is a front view of ULTIMA II with part of the enclosure removed. It shows the three mercury columns mounted on a stainless steel mounting plate. The bottom closures with ultrasonic transducers are mounted underneath the mounting plate and are not visible in the photo. A typical bottom closure is shown schematically in Fig. 3. The three mercury columns are connected at the bottom through the stainless steel tubes and fittings protruding from the mounting plate. There is a provision for draining the mercury. The space above the top of the outer mercury columns is connected on the outside to the pressure port. The center column is connected to a reference vacuum pumping system. The bellows on top of the tubes are needed to adjust for slight misalignment of the plumbing.

The glass tubes have an internal diameter of about 75 mm and are 100 mm and 140 mm long respectively. They are sealed with polytetrafluoroethylene washers. A thin layer of chromium is vacuum deposited on the inside of the tubes to neutralize electrostatic charges on the glass, which may cause discontinuous variations of the surface tension.

Fig. 4 shows some of the ancillary equipment. In front of the manometer box are the three circulators used to feed electrical signals into and out of the transducers. Behind the manometer are the control panel and the pumping systems. The reference pumping system consists of an oil pump and a mercury diffusion pump. The test pressure system uses helium. Helium can be bled into the system through suitable valves and a screw pump, or it can be withdrawn with the help of a separate fore pump.



Dual channel phase sensitive detection of echo sequence with 90° phase difference between reference channels.

FIG. 6

THE INTERFEROMETER

Fig. 5 is a schematic of the RF part of the electronics. The RF-oscillator is a crystal controlled oscillator that supplies a 10 MHz signal to the gated amplifier (RF switch followed by power amplifier) and to the detectors. From the gated amplifier the signal is routed to the mercury column (sample) through a circulator (not shown). The output signal from the mercury column is fed to the amplifier - a high-gain, turn receiver - and then to the phase sensitive detectors. The resulting signal is given in Fig. 6, where the echo train is shown after phase sensitive detection in the two detectors.

The amplifier (receiver) performs an additional function: It demodulates the RF pulse echo train and generates a logic level pulse for each echo. The process controller uses these pulses to count down to the desired echo. The amplitudes of the phase sensitive detected signals for a given echo determine the size and polarity of the component vectors discussed in the section on "Basic Theory" in connection with Fig. 1. The amplitudes of the selected p-th echo are sampled, held, measured, converted to digital code and stored for further use.

This process of transmitting a pulse, receiving and processing the echo, and storing the information is successively applied to each of the three columns. One such scan is made every ten milliseconds and each time the stored data is updated. If the sign of one of the component vectors changes from one scan to the next, the respective up/down counter is updated. The stored data can be printed out on a teletype for further processing.

THE PROCESS CONTROLLER

The timing and signal processing functions of the instrument are under the control of an Intel 4040 microcomputer. In addition to interfacing with a MIDAS data acquisition system the microprocessor also monitors the system performance to detect and compensate for the effect of external disturbances, that would lower the reliability of the system.

In detail the microprocessor performs the following functions:

Start

Set multiplexer to column 1

Trigger the gated amplifier

Count down to preset echo

Sample and hold component vectors

Measure time of flight and compare with previous reading. If within tolerance, proceed; if out of tolerance, wait 2 ms and return to "Trigger"

Meaure component vectors, convert and store result

Update up/down counters

Repeat for columns 2 and 3

Test for MIDAS command; if no MIDAS command is present, go back to "Set", if present, stop system and move data taken during last scan from storage to the MIDAS system's teletype; then go back to "Set".

It is conceivable in the future to use the microprocessor also to compute the instantaneous pressure from the raw data. At the present time all further data processing is done on a UNIVAC 1108 digital computer.

OUTPUT DATA

An example of the data printed out on the teletype is reproduced in Fig. 7. The first six columns contain from left to right: the two component vectors for mercury column 1, those for mercury column 2 and those for mercury column 3; the next three columns contain the fringe counts for the three mercury columns. The next to last column contains the temperature of the manometer in 10^{-2} °C and the last column gives the time of day.

When these data were taken all three mercury columns were in equilibrium position, the interferometer operated on the second echo, and data were read out once every 30 seconds. From these data the actual differential height of the mercury columns was calculated. In the present case the average differential height was about zero. The data listed in Figs. 8 and 9 are therefore indicative of the stability of the system under equilibrium conditions. Listed in Fig. 8 are the time and the calculated lengths of the three columns in micrometers. The slight differences in the initial lengths drop out of all further calculations, since only changes in column lengths need to be considered. The fluctuation of the three lengths listed in Fig. 8 is of the order of a few tenths of a micrometer. From these three column lengths the indicated pressure is calculated. Listed in Fig. 9 are the time, the temperature of the manometer and the pressure in micrometers of mercury and in Pascal. The standard deviation of the third column is about 0.25 micrometer of mercury. This is presently the limit of resolution. It appears that the fluctuation of the indicated pressure is caused by vibrations of the surface of the mercury columns, which is turn are due to structure borne sound from the pumping system and from the building.

ULTIMA II TRIAL RUNS
EQULIBRIUM POSITION
PUMPED
THERMALLY LAGGED WITH BOX 1 ONLY
30 S INTERVAL

COLUMN LENGTHS IN MICROMETERS :

TIME	COL. 1	COL. 2	COL. 3
162541.00	59992.997	59994.809	59996.534
162610.00	59992.997	59994.895	59996.966
162645.00	59993.083	59995.067	59996.275
162711.00	59993.083	59994.809	59996.362
162741.00	59993.083	59994.636	59996.275
162811.00	59993.083	59994.895	59997.396
162841.00	59992.897	59994.881	59996.521
162912.00	59992.811	59994.623	59996.435
162939.00	59992.997	59994.722	59996.966
163010.00	59993.170	59994.981	59997.052

FIG. 8

ULTIMA II TRIAL RUNS
EQUILIBRIUM POSITION
PUMPED
THERMALLY LAGGED WITH BOX 1 ONLY
30 S INTERVAL

FLUCTUATION OF INDICATED PRESSURE

TIME	TEMP.(C)	P (UMHG)	P (PA)
162541.00	23.460000	.042968750	.0057012635
162610.00	23.460000	-.086425781	-.011467314
162645.00	23.460000	.38818359	.051505733
162711.00	23.460000	.085937500	.011402527
162741.00	23.460000	-.042968750	-.0057012635
162811.00	23.460000	-.34472656	-.045739682
162841.00	23.470000	.17236328	.022869800
162912.00	23.470000	0.	0.
162939.00	23.460000	-.25927734	-.034401942
163010.00	23.460000	-.12939453	-.017168578

* (UMHG) = MICROMETER OF MERCURY COLUMN

FIG. 9

ERRORS AND UNCERTAINTIES

Several sources of error have been discussed in past reports, but we shall review only the uncertainty caused by temperature as the main source of error

The pressure indicated by the manometer is calculated from

$$p = g \rho H \tag{8}$$

where p is the pressure in [Pa], g is the acceleration due to gravity in [m/s^2] ρ is the density of mercury at the appropriate temperature in [kg/m^3] and H is the difference in meniscus heights in [m].

The error in p caused by the temperature measurement can be expressed as follows, if the temperature is uniform throughout the entire manometer:

$$dp = g H \; d\rho + g\rho \; dH \tag{9}$$

$$d\rho = \rho_0 \; \alpha_\rho \; dT \tag{10}$$

$$dH = \{\tfrac{1}{2}(m_1 + m_3) - m_2\} \frac{c_0 \alpha_c}{8pf} \; dT \tag{11}$$

where α_ρ , α_c are the thermal coefficients of density and of speed of sound,

c_0 is the speed of sound in mercury,

m_1, m_2, m_3 are the fringe counts including the fractional values,

dT is the uncertainty in the temperature determination.

With an indicated pressure of 15 kPa (about 110 mmHg) an uncertainty of dT = 0.01 °C causes an uncertainty in the pressure of

$$dp = 2.7 \times 10^{-2} + 4.6 \times 10^{-2} \text{ [Pa]}, \; dp/p = 4.2 \text{ ppm} \tag{12}$$

the first term deriving from the temperature effect on density, the second from that on the speed of sound.

Generally the temperature is not uniform throughout the manometer and a more realistic uncertainty statement is

$$(13) \qquad dp = g \sum_{i=1}^{3} \quad L_i \quad {}_{o}\alpha \; + \; (m_o + m_i)\,\frac{c_o \alpha_c}{8pf} \quad dT,$$

which, for the same column lengths as above, renders

$$(14) \qquad dp = 4.3 \times 10^{-2} + 7.6 \times 10^{-2} \quad [Pa]$$

$$dp/p = 7.9 \text{ ppm}$$

for $\qquad dT = 0.01°C.$

The absolute uncertainty given in equs. (12) and (14) is independent of pressure. Consequently the relative uncertainty will increase rapidly at lower pressures.

PROBLEMS

Trial runs have only just been started and it is therefore difficult to predict problems that might show up. The manometer has responded very well to pressure changes and has returned to the equilibrium position to within a fraction of a fringe.

When the manometer is left in the equilibrium position under vacuum there appear to be disturbances about once every 8 to 12 hours. These may be caused by a very slow leak or by the diffusion of helium from the seals, walls or even the mercury. This is the first problem under study now.

ULTIMA II TRIAL RUNS
EQUILIBRIUM POSITION
PUMPED
THERMALLY LAGGED WITH BOX 1 ONLY
30S INTERVAL

DATA FROM MIDAS SYSTEM

VECTOR 1		VECTOR 2		VECTOR 3		COUNT 1	COUNT 2	COUNT 3	(C)	TIME
069	020	035	-050	-051	038	0000000	-0000000	0000000	2346	162541
068	020	036	-050	-053	034	0000000	-0000000	0000000	2346	162610
069	021	036	-047	-049	040	0000000	-0000000	0000000	2346	162645
069	021	035	-050	-050	040	0000000	-0000000	0000000	2346	162711
069	021	034	-051	-049	040	0000000	-0000000	0000000	2346	162741
068	021	036	-049	-055	029	0000000	-0000000	0000000	2346	162811
068	021	037	-047	-052	036	0000000	-0000000	0000000	2347	162841
069	020	034	-049	-051	037	0000000	-0000000	0000000	2347	162912
068	020	034	-050	-053	034	0000000	-0000000	0000000	2346	162939
068	022	037	-049	-054	033	0000000	-0000000	0000000	2346	163010

FIG. 7