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MULTI-CHANNEL PRESSURE TELEMETRY SYSTEM FOR BASE PRESSURE MEASUREMENTS ON SMALL MODELS

George S. Pick, et al

David W. Taylor Naval Ship Research and Development Center
Bethesda, Maryland

July 1975

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by

George S. Pick and Samuel E. Dawson

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MULTI-CHANNEL PRESSURE TELEMETRY SYSTEM FOR BASE PRESSURE MEASUREMENTS ON SMALL MODELS

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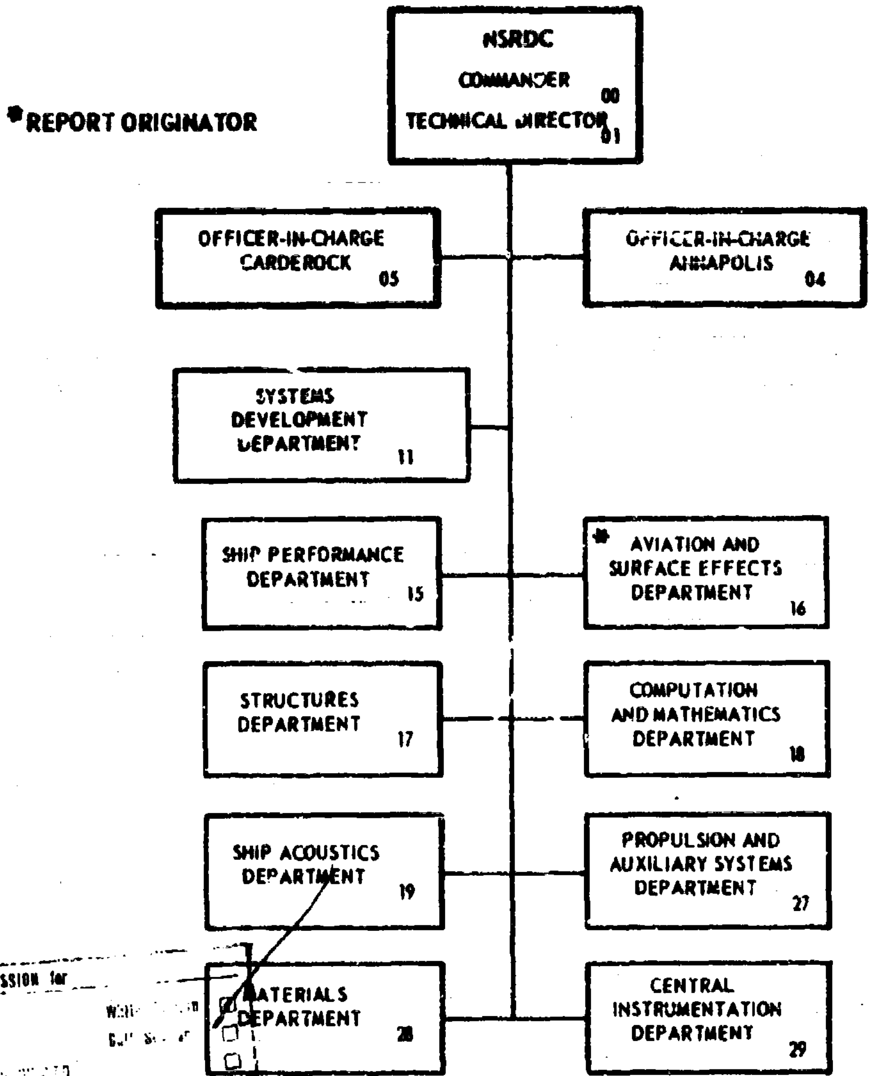

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The results showed that the interaction increases approximately as the inverse square of the distance. The center frequency spread has the most significant effect on the interaction. If 7MHZ or larger frequency spacing is maintained the maximum error is ±8 percent for the pressure range of 0.5 to 2 0 mm Hg. The measured data can be corrected by an interaction matrix method and yield errors in the order of a few percent depending on the accuracy of calibration.

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ABSTRACT

Effects of close proximity on simultaneously operating transducer-telemetry units had been systematically evaluated. Parameters such as the interaction as function of transducer-to-transducer distances, center frequency spread and its effect on the interaction, change of sensitivity in relation to center frequency, center frequency shifts as functions of transducer-to-transducer distances, and the effects of common power supply and shielding have been evaluated.

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INTRODUCTION

There is considerable interest in the base flow characteristics of missiles and aircraft. Unfortunately, these characteristics cannot be accurately determined by the usual wind-tunnel techniques since the data must be free of model support interferences. A possible alternative involves telemetering the data from free-flying, magnetically-suspended, or thin-strap-supported models. In small wind tunnels where there are severe limitations on model size, telemetering several pressures or temperatures simultaneously results in problems associated with the effects of close proximity of the transducer-telemetry units. The systematic evaluation and the possible elimination of these effects is the subject of the present investigation.

Parameters such as the interaction as a function of transducer-to-transducer distances, center frequency spacing and its effect on the interaction, change of sensitivity in relation to center frequency, center frequency shifts as functions of transducer-to-transducer distances, and the effects of common power supply and shielding have been studied.

Four low-pressure transducer-telemetry units which were specially made by the Jet Propulsion Laboratory based on R. G. Harrison's design (Reference 1) were used in the study.

Although the present work does not contribute to the advancement of telemetry circuit design or fabrication technology, it is believed to be the first attempt to systematically evaluate the effects of close proximity. In this respect the authors wished to complement the earlier works of Harrison (Reference 1) and Choate (Reference 2) who independently developed and tested the units capable of measuring pressures and heat transfer in free flight wind tunnel models over wide speed ranges and accelerations. However, Harrison used a single unit in his model and Choate's models were quite large (3.8 and 4.8 inch base diameter, 9.2 and 11.3 inches long) compared to the model size used in the present investigation (2 inch base diameter, 6 inches long) so interaction due to close proximity did not play a significant role.

DESCRIPTION AND CALIBRATION OF EQUIPMENT

Transducer Calibration System

The transducer-telemetry units were calibrated in a specially built low pressure system consisting of two portable high vacuum pumping stations, a precision bleed-in valve, a precision electronic manometer and assorted conduits. The schematic diagram of the apparatus is shown in Figure 1.

The main system consists of a mechanical vacuum pump which serves to back up a four-inch diffusion pump with pumping capacity of 400 liters/second and ultimate vacuum capability of 1×10^{-7} mm Hg. The mechanical vacuum pump is vibration insulated from the high vacuum port of the apparatus. The high vacuum port is equipped with a gate valve, to separate it from the diffusion pump, a roughing line and assorted valves, to connect it with the mechanical vacuum pump, and a vent line and valve. The absolute pressure in the chamber is measured by an ultra-stable Bayard-Alpert type ionization gauge. Two thermocouple gauges measure the diffusion pump exhaust pressure and the mechanical pump intake pressure. A solenoid operated vent valve provides automatic opening and closing at start-up for the mechanical pump.

The vacuum instrumentation is not used in the calibration procedure itself, but merely provides a means of observing that the system is below some prescribed critical pressure level.

The transducers, to be calibrated in the low pressure environment, are placed in a bell jar atop the high vacuum port of the diffusion pump. It was found that the sealing action of the Dow Corning high vacuum silicone grease between the ground glass surface of the bell jar and the stainless steel flange of the high vacuum port is sufficient to achieve vacuum levels in the order of 7×10^{-7} mm Hg after a few hours of pumping.

Controlled air bleed-in is achieved through a calibrated Granville-Phillips 203 Variable Leak. It contains no organic seals thus eliminating outgassing and contamination. Conductance of the Variable Leak is continuously variable from 10^{-10} cm^3/sec (standard pressure and temperature) to 100 cm^3/sec (standard pressure and temperature) with atmospheric pressure on the inlet port. When closed, the leakage conductance is less than 10^{-13} cm^3/sec.

The pressure standard used in the calibration system is a Datametrics type 1014 Electronic Manometer and type 511-3 Barocel capable of measuring pressures between 0 and 1.0 psi (51.7 mm Hg) on seven consecutive db ranges from 0 to 0.001 psi to 0-1 psi range. For the present measurements, a digital voltmeter was utilized to permit precisions of approximately $\pm$0.1 percent of full scale in each range (0.0001 percent of the full scale of the transducer at the lowest range of 0 to 0.001 psi) with $\pm$0.01 percent resolution.

The digital voltmeter is (EAI Type 5000, Model 26.138. This unit has an absolute accuracy of 0.02 percent of full scale and an input impedance greater than 100 MΩ on the 9.999 volt full scale range) connected to the external d.c. output poles of the electronic manometer.

This provides a zero to five V d.c. full scale output on each of the ranges.

Transient response time of the d.c. output voltage is two milliseconds. The instruments have negligible hysteresis (0.005 percent maximum excursion), and continuous resolution. The drift, even on the most sensitive ranges, is extremely small (less than ±0.01 percent). The linearity of the Barocel is from ±0.1 percent to 0.05 percent on all range positions except the 0-1 psi range where it is ±0.3 percent full scale. The noise level is less than 0.05 percent full scale. The temperature effect of zero is less than 5×10^{-4} percent per degree F. on any sensor range, or the sensitivity it is 0.01 percent of reading per degree F.

The electronic manometer and the pressure sensor was calibrated by the National Bureau of Standards to within ±0.05 percent. The calibration lines for the 0-0.1 psi and 0-0.03 psi scales are shown in Figure 2.

A Veeco Model VS-9 high vacuum pumping station equipped with a two-inch diffusion pump provides constant low reference pressure on the reference port of the Barocel. This pressure is continuously monitored on the built-in instruments of the VS-9 system and does not exceed 5×10^{-5} mm Hg.

During the assembly of the vacuum calibration system extreme care was taken to insure minimal leakage and outgassing. The measured outgassing rate of the assembled system without the transducers was 0.004 μ/sec with the variable leak at closed position. When all the transducers were installed this combined outgassing and leak rate increased to 0.008 μ/sec. The ultimate vacuum in this configuration, after several hours of pumping, was determined to be 5×10^{-6} mm Hg. The leak rate was a near exponential function of time as illustrated in Figure 3.

The correlation equation may be expressed analytically within ±2 percent as

$$P = AT^{B}+C$$

where

P is in microns and T is in seconds.

The variable leak calibration showed that below the counter setting of 55, the leakage rate through the valve was negligible, between 65 and 75 it increased from 10^{-3} mm Hg/sec to 1.5×10^{-1} mm Hg/sec, again as a near exponential function of time.

Since the outgassing and leakage rates were small, stable running times of the order of 60 seconds were achieved without pressure corrections for leakage rate even for pressure measurements of 0.5 mm or less, since even at this pressure the leakage contributed less than 0.1 percent of the measured pressure.

Telemeter-Transducer Units

The low pressure transducer-telemetry units were specially made by the Jet Propulsion Laboratory based on R. G. Harrison's design.

The telemeters utilize an ultra stable Colpitts oscillator operating at center frequencies between 106 and 137 MHZ; its stability was found to be 0.5 percent of 200 KHZ for a period of one minute. The oscillator is frequency modulated by the variable capacitance-type pressure transducer. The telemeter assembly consists of four major components: a printed circuit inductor, variable capacitance-type differential pressure transducer, battery package, and all other circuit components in a microminiature package of pellet-type construction. The transducer sensing element is a prestressed thin (0.00025 inch thick) metal diaphragm soldered over the reference port case and separated electrically from the pressure port. The stress level of the diaphragm determines the sensitivity of the unit. The diaphragm and the inner surface of the pressure port form the variable parallel plate capacitor. The various components of the unit were rigidly encapsulated in epoxy potting to provide thermal isolation and shock resistance.

The rise time of the pressure telemeters is 0.5 msec, or better, without tubing. Their thermal stability was reported to be good. Harrison found that a temperature increase of 100°F at atmospheric pressures produced a 2.7 percent increase in the oscillator frequency and 0.1 percent change in the full scale sensitivity calibration. The temperature-time lag was about three minutes. There were little, or no changes in the telemeter performance over a temperature range of

30 to 200°F.

Outside dimensions of the pressure telemeter unit were 0.67 inches in diameter and 0.51 inches in length. The schematic diagram of the oscillator circuit is shown in Figure 4 and the photograph of a unit is shown in Figure 5.

For the detailed performance characteristics and construction of these units the reader is referred to Harrison's report (Reference 1).

Instrumentation

Figure 6 shows the block diagram for a single channel of telemeter instrumentation. The antenna used was a 120 MHZ half wavelength folded dipole. The antenna was matched to the coaxial cable using a Blonder-Tongue Model MT-283 matching transformer. Two Jerrold Model 3440 preamplifiers were then used in cascade to obtain at least 40 db gain for driving the Jerrold Model UT 22W signal tap-offs. Four of the tap-offs were used to couple the input signals to the four FM receivers. Resulting isolation was at least 31 db and feed-thru losses were less than 0.25 db for the frequency range from 100 to 140 MHZ.

The tuners used are the same McIntosh Model MR71 type used in Reference 1. The RF and oscillator stages of these tuners have been modified to provide reception in the band from 100 to 140 MHZ. The output signal is taken from the discriminator test jack. At this point a typical deviation sensitivity was 71 KHZ/volt with an output linearity of ±2 percent over the range from -1.5 to 2.5 volts. A Sorensen Model ACR1000 AC voltage regulator was used to maintain tuner line voltages within ±0.1 percent. Tuner outputs were then fed into four Beckman Model C-44 Amplexer Amplifiers which in turn drove the 600 HZ type 7-323 galvanometers in a C.E.C. type 5-124 recording oscillograph. The amplifier-galvanometer combination gave best line d.c. linearities of less than ±1 percent of two inches deflection.

Other instrumentation included a Triplett Model 3432-A signal generator and a Fairchild Universal Counter/Timer Model 8200 used in calibrating the FM receivers. Counter error amounted to less than ±3 KHZ over the 100 to 140 MHZ range. In addition an EIA analog computer Model TR 10 was used to scale and divide tuner output voltages to obtain a voltage proportional to transducer interaction. The division circuit used a "quarter-square" type of multiplier in the feedback circuit of a high-gain amplifier. The overall circuit gave 13.6 x/y volts out within ±2 percent for outputs less than 10 volts and inputs x and y greater than 0.1 volts.

Component Calibration

Each FM receiver was calibrated at three points within its frequency range. Because a frequency limitation of 12.5 MHZ in the available counter the tuners were calibrated using the 10th and 12th harmonics in the signal generator output. The output voltage from the discriminator was displayed on a digital voltmeter. With zero discriminator output the signal generator was adjusted to give a reading of 5 on the tuner signal strength meter. The tuner automatic frequency and muting controls were left in the off position. A typical tuner calibration curve exhibits ±2 percent linearity over the range from -1.5 volts to 2.5 volts with slope values repeatable within ±2 percent.

The galvanometer drive amplifiers and recording oscillograph were calibrated as a unit and show typical linearities of less than ±1 percent with calibration repeatability within ±0.4 percent.

TEST PROCEDURES

Telemeter Calibration

The telemeter units were placed individually in a bell jar and allowed to stabilize following evacuation of the system to around 5μ absolute pressure. A block diagram of the calibration system is shown in Figure 6. A sample of the oscillograph record of the calibration data is shown in Figure 7 and the photograph of the overall system is shown in Figure 8. The reference leak rates were such that about 5 minutes were required for pressure stabilization. The pressure measuring system was then zeroed and the vent valve closed. The precision leak was opened to allow the associated piping volume to bleed up to pressures in the range from 24 to 96 mm relative to the reference vacuum system. The roughing valve was then closed and the vent valve opened giving telemeter differential pressures in the range from 0.5

to 2.0 mm. Owing to the pipe length between the vent valve and the bell jar, about 0.5 seconds were required for the bell jar pressure to stabilize. This delay resulted in a loss of calibration trace deflection amplitude arising from the reference port leak rate.

A correction for this effect was determined by first allowing an initial telemeter differential pressure of about 2 mm to decay toward zero. The oscillograph trace of the decay was then divided into a number of increments and the slope of each increment tabulated against an average deflection. The average deflection values were then superimposed on the oscillograph trace of the pressure calibration step. The intersections of these points with the calibration curve were then extended to the time axis and each time increment thus formed was multiplied by the corresponding slope value. These incremental corrections were then graphically integrated up to the time corresponding to maximum calibration trace deflection. The total correction expressed as a percentage of the maximum calibration trace deflection remained essentially independent of the pressure step magnitude.

Interaction for Two Telemeters in Close Proximity

Preliminary telemeter interaction studies were made under atmospheric conditions using two units with axes spaced from 0.68 to 1.44 inches apart. A plastic mounting plate was used to hold and position the transducers. The units were unshielded and were powered from a common mercury battery supply. Figure 9 shows a block diagram of the system used. The analog computer was used to provide an oscillograph deflection proportional to the scaled ratio of the outputs from the two telemeter channels.

Interaction for Three Telemeters in Close Proximity

Interaction studies were next made under atmospheric conditions using four telemeter units located within the calibration model which consists of a removable teflon core surrounded by an 1/8 inch thick aluminum skin as shown in Figure 10. The axes of the three base telemeters were on a 0.78 inch diameter circle (printed circuit antenna boards 0.06 inches apart). The base telemeter center frequencies were

116, 125, and 135 MHZ. The fourth telemeter, located inside the model in front of the three base units, had a center frequency of 108 MHZ. After obtaining the interaction versus pressure relations the model was placed in the bell jar and calibrated in the same manner as for the single telemeter case.

RESULTS AND DISCUSSION

Individual Telemeter Calibration

With center frequency held fixed, sensitivities for the individually tested telemeter units repeated within ±6 percent. In obtaining these sensitivities the output data from two FM receivers were considered.

In the case of telemeters #2 and #4 the sensitivities calculated from one tuner channel are consistently 3 to 4 percent higher than those obtained from the other. This indicates a need to improve the tuner deviation sensitivity stability with time and temperature. In addition the 0.6 mm pressure sensitivities for telemeters #1 and #4 are consistently 1 percent to 3 percent lower than the average sensitivities for the 1.0 to 2.0 mm range. These units also show an apparent diaphragm overshoot and slow return to zero following a pressure pulse.

The variation in telemeter sensitivity with frequency is shown in Figure 11. These curves include reference port leak rate corrections ranging from 0.8 to 5.2 percent. For projected future use the errors associated with leak rate correction will be eliminated by tying the reference ports to a closed, common reference volume.

A set of theoretical slopes which are also shown in Figure 11 are those obtained from the relation $\omega_i = \sqrt{1/L_i C_o}$ where it is assumed that the total frequency determining capacitance C_o remains constant and only the inductance L_i is varied to obtain the new operating frequency ω_i. Under these conditions the sensitivity variation would be directly proportional to frequency. This simplified procedure seems to be in fair agreement with the measured result. In practice, however, the telemeter center frequency was increased by shunting an increasing portion of the printed circuit inductor with a fine wire. This technique apparently caused enough variation in stray capacitance to significantly change C_o. This effect could also account for some of the sensitivity variations observed in repeat calibrations.

Interaction for Two Telemeters

For the case of two transducers in close proximity Figure 12 shows the interaction variation with center frequency spacing. Figure 13 shows the generally large increase in interactions obtained for decreasing telemeter separation. A typical oscillograph trace showed these interaction magnitudes to be essentially independent of the pressure differential across the disturbed transducer. For values of interaction below about 1 percent the effects of tuner and telemeter zero drift produced masking errors in the division circuit output. In this case a more repeatable value was obtained by taking ratios of peak-to-peak deflections from the separate channel traces.

The use of separate power supplies and shielding reduced the interactions somewhat but not as significantly as increased center frequency spacing. In addition the more effective shielding geometries reduced the signal strength and produced large detuning outputs for very small relative motions between the shield and telemeter. In the unshielded case there are also large proximity detuning effects as shown in Figure 14.

Interaction for Three Telemters

If several telemeter units are sufficiently far apart the interaction effects between them may be neglected and the measured pressures regarded as true values. On the other hand, if the interaction effects are not negligible, and such is the case in the present study, the measured pressures will be linear functions of the interaction between the transducer-telemeter units in the model.

In the general case the corrected pressures would have to be obtained from the simultaneous solution of the following equations:

$$P_1^1 = P_1 I_{11} + P_2 I_{12} + P_3 I_{13} + \dots\dots\dots\dots$$

$$P_2^1 = P_1 I_{21} + P_2 I_{22} + P_3 I_{23} + \dots\dots\dots\dots$$

$$P_3^1 = P_1 I_{31} + P_2 I_{32} + P_3 I_{33} + \ldots\ldots\ldots\ldots$$

$$P_j^1 = P_1 I_{j1} + P_2 I_{j2} \ldots P_j I_{jk} + \ldots\ldots\ldots\ldots$$

where P_j^1 $j = 1 \ldots j$ are the uncorrected measured pressures, P_j are the actual (or corrected) pressures, and I_{jk} are the interaction coefficients with $I_{jk} = 1$ for $j = k$.

In the present study three telemeter units were installed in the calibration model base area and a fourth telemeter was located inside the model. The fourth unit showed no measurable interaction with the three base units. The measured interactions for the base telemeters ranged from -2.0 to 4.3 percent. In some cases the percentage interactions varied with pressure. Under these conditions the interaction components were obtained from curves of pressure versus percent interaction.

Measurements conducted in the calibration system between the 0.5 to 2 mm Hg range showed that maximum errors in the interaction corrected pressure varied from -1.5 to 4.3 percent. Since in this case all the units measured known calibration pressures the general equations could be simplified and the corrected pressures were obtained from the relations:

$$P_1 = P_1^1 - P\,(I_{12} + I_{13})$$

$$P_2 = P_2^1 - P\,(I_{21} + I_{23})$$

$$P_3 = P_3^1 - P\,(I_{31} + I_{32})$$

where

P is the known input pressure.

The fact that errors exist between the corrected pressure calculation and the known input pressure points out the need for greater absolute accuracy in the measurements before testing the general case.

CONCLUSIONS AND RECOMMENDATIONS

An attempt has been made to evaluate systematically the effects of close proximity on simultaneously operating transducer-telemetry packages. The techniques of calibration, instrumentation and interaction data evaluation are applicable to similar systems investigations.

Perhaps the most significant result is the demonstration that several of the transducer-telemetry units can function together in close proximity and yield useful results even without applying interaction corrections. The uncorrected data exhibit maximum errors of 8 percent for the pressure range of 0.5 to 2 mm Hg for center frequency spread between the units of 7 MHZ or larger. It was also shown that beyond this value, further spread apparently will not result in much less interaction since beyond this point the interaction curves show rather slow convergence toward zero. In very close proximity the interaction increases approximately as the inverse square of the distance. Maximizing the size of the model would be an effective way to reduce interaction. If one must cope with the interaction problem due to limited model size, it is believed that the interaction matrix method suggested in the present paper will yield useful data within a few percent depending on the accuracy of calibration. This is a great improvement from the uncertainties of reported base pressure results in the literature (for example, Muntz, et al, (Reference 3)).

The further miniaturization of the electronic circuitry and the addition of buffer circuits promises further reduction or perhaps elimination of the interaction problem.

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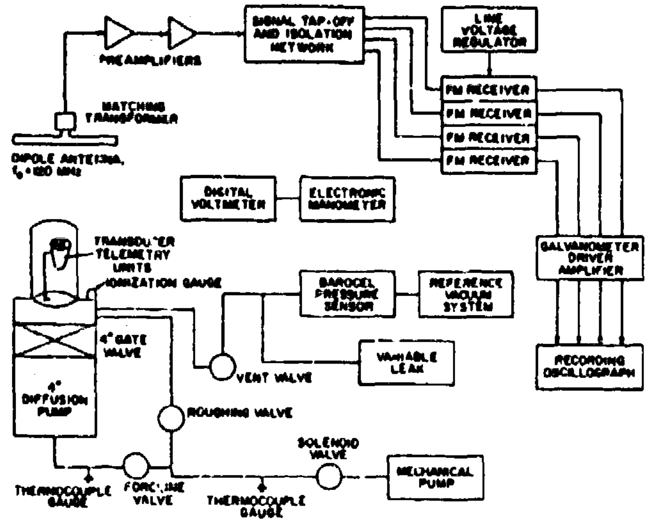

Figure 1 - Schematic Diagram of Calibration System

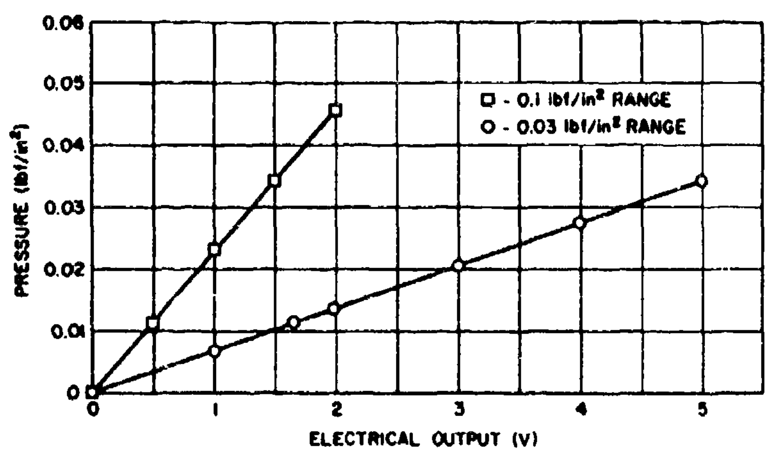

Figure 2 - Barocel Calibration Curves

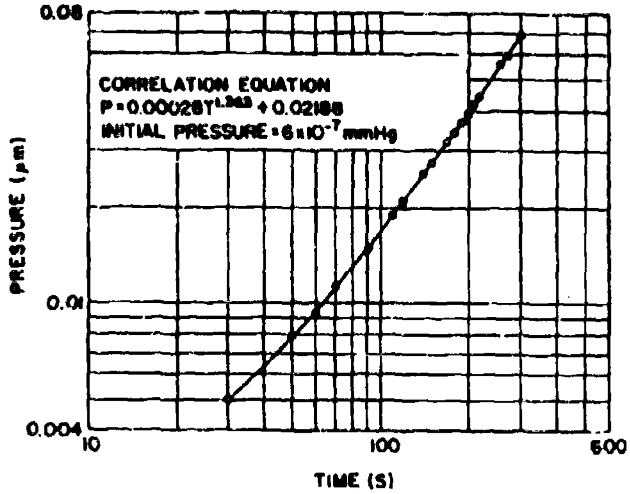

Figure 3 - System Leak Rate Without Calibration Package

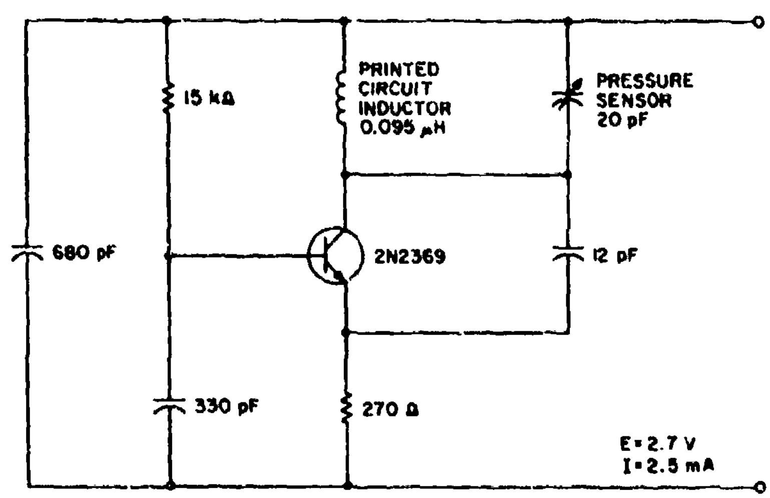

Figure 4 - Schematic Diagram of Telemeter Oscillator

Figure 5 - Close-up of Telemeter-Transducer Unit

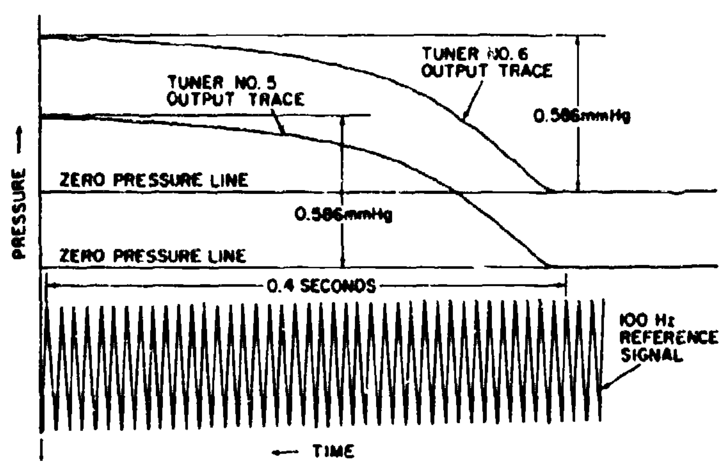

Figure 6 - Typical Pressure Calibration Data

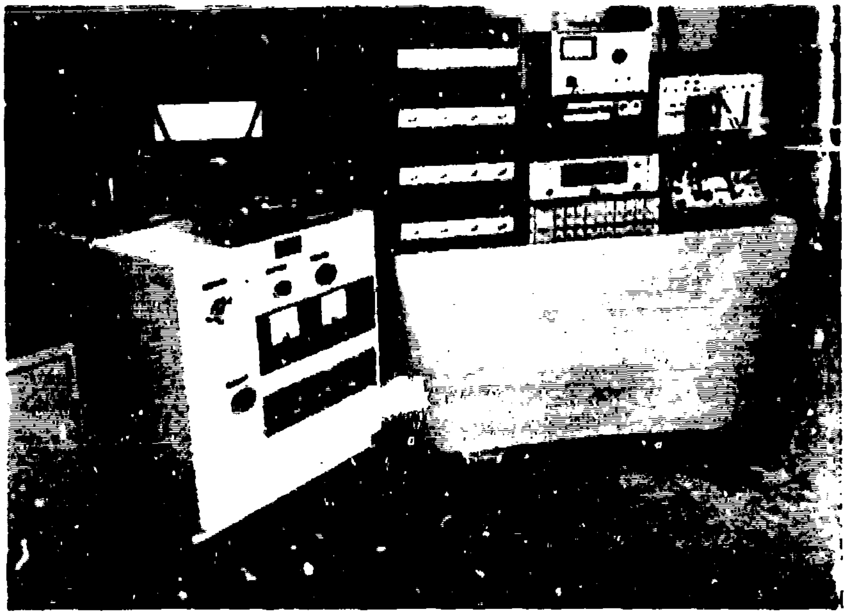

Figure 7 - View of Complete Calibration System

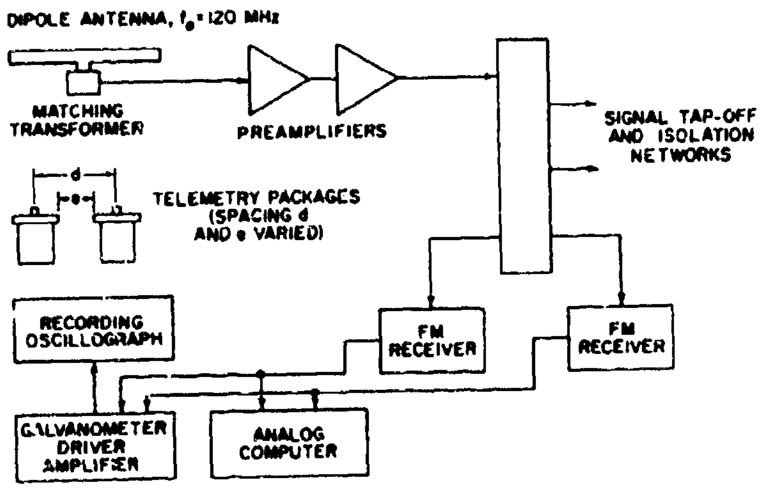

Figure 8 - System for Interaction Studies

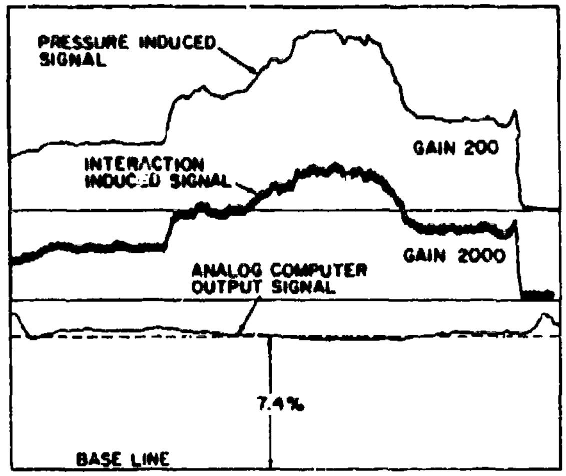

Figure 9 - Typical Interaction Traces

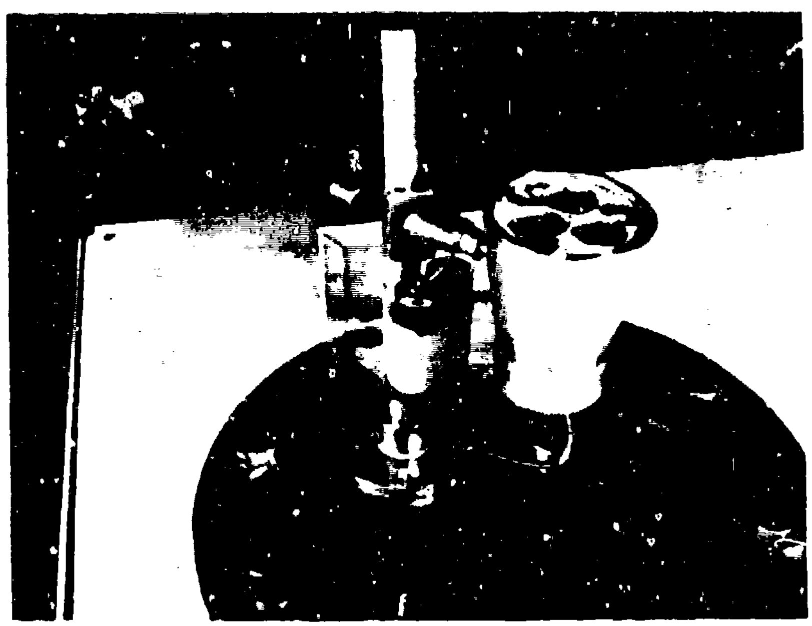

Figure 10 - View of Calibration Model

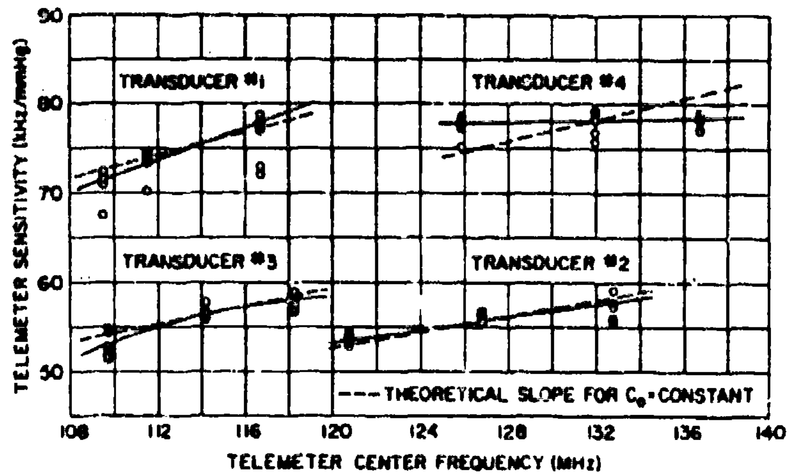

Figure 11 - Variation of Telemeter Sensitivity with Frequency

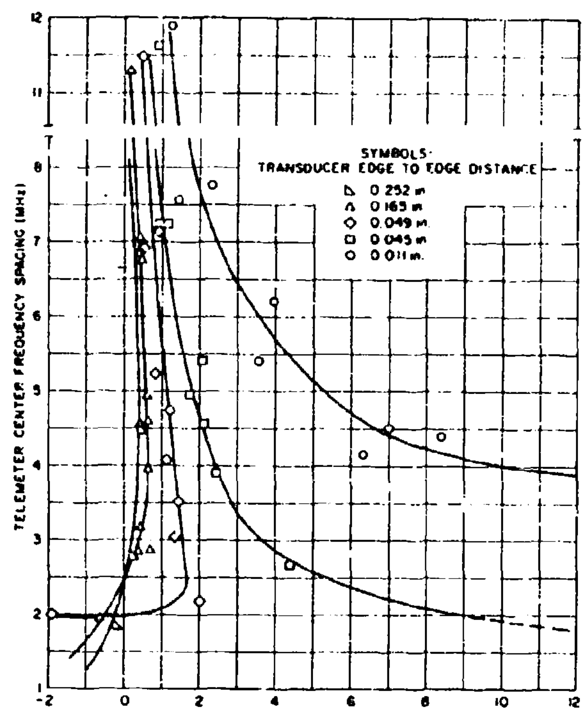

Figure 12 - Interaction as Function of Center Frequency Spacing

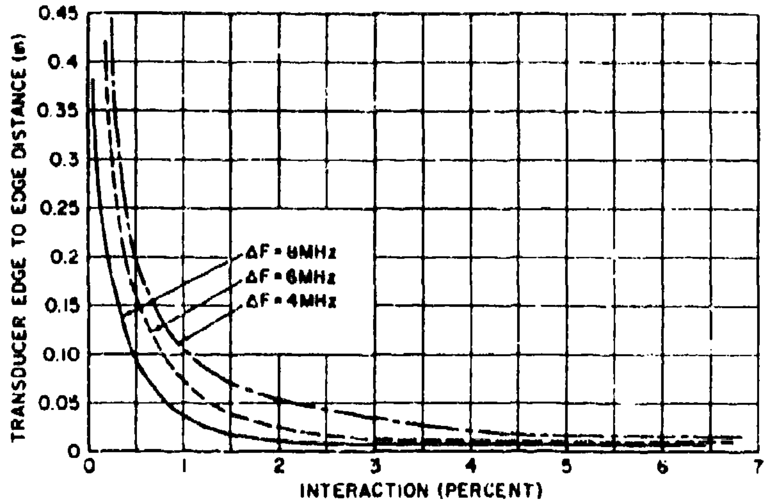

Figure 13 - Interaction as Function of Telemeter Edge-to-Edge Distances

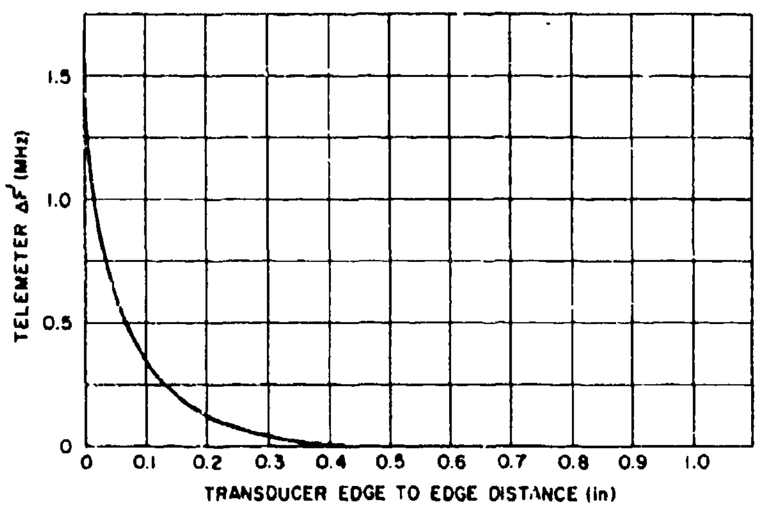

Figure 14 - Proximity Detuning Effects for Two Telemeters