T H E U N I V E R S I T Y O F M I C H I G A N
COLLEGE OF ENGINEERING
Department of Electrical Engineering
Space Physics Research Laboratory

Technical Report No. 1

THE ACOUSTIC WIND MEASUREMENT: A SIX MONTH SUMMARY

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INTRODUCTION

This report summarizes the results of work up to the mid-term of the contract period, about July 30, 1966. The contract scope of work paragraph specifically outlines the nature of the research to be performed.

1. Define the requirements of a permanent sound ranging station. The basic plan of the station would be similar to that of the existing, already proven station. The permanent station would include features to make it amenable to experimentation and adaptation of improved techniques as they are developed.

2. Continue measurements during the Saturn series of launches with the existing system while the permanent station is being constructed.

3. Reduce the recorded data from all Saturn flights during the contract period.

4. Investigate methods and define a technique for electronic cross correlations of the data to lead to an automatic data reduction system.

5. Conduct experimental and theoretical studies to improve the measurement technique. These studies will include but not be limited to the following:

    a. Use of higher frequency microphones to minimize error in determining sound arrival times.

    b. Methods of reducing ground wind interference.

    c. The extent of the finite amplitude effect and development of a method to account for it.

    d. The relevant characteristics of the source of the exhaust noise and its location with respect to the vehicles.

The tasks numbered 1,2,3,4 and 5a have either been started or completed and will be reported here. The report is divided into three sections: Data (2 + 3), Data Analysis (4) and Capacitor Microphones (5a).

It was mutually agreed between the M.S.F.C. contract technical monitor and S.P.R.L. that the engineering requirements for the permanent sound ranging array (1) should be general, rather than detailed, specifications. This is expected to reduce the ultimate cost and expedite the installation by extending some flexibility in choice of equipment and services as situations are encountered and evaluated in the field. These requirements were defined and forwarded in letter form to M.S.F.C.

DATA

During this reporting period acoustical monitoring was performed for the AS-201 and AS-203 launches. The wind profiles determined from AS-201 are presented in Fig. 5. Data from earlier launches is included for completeness. SA-8, SA-9, and SA-10, winds were measured up to first stage burnout which occurred at approximately 85 km. The sound level at the ground from the second stage was not sufficiently intense to be useful for wind data.

In the case of Ranger 8, the trajectory was such that the vehicle was 100 km distant when it was only 45 km high. Thus, the sound faded into the background noise level before very high altitudes were attained.

The AS-201 first stage burnout occurred at about 60 km and the second stage did not generate sufficient sound to allow

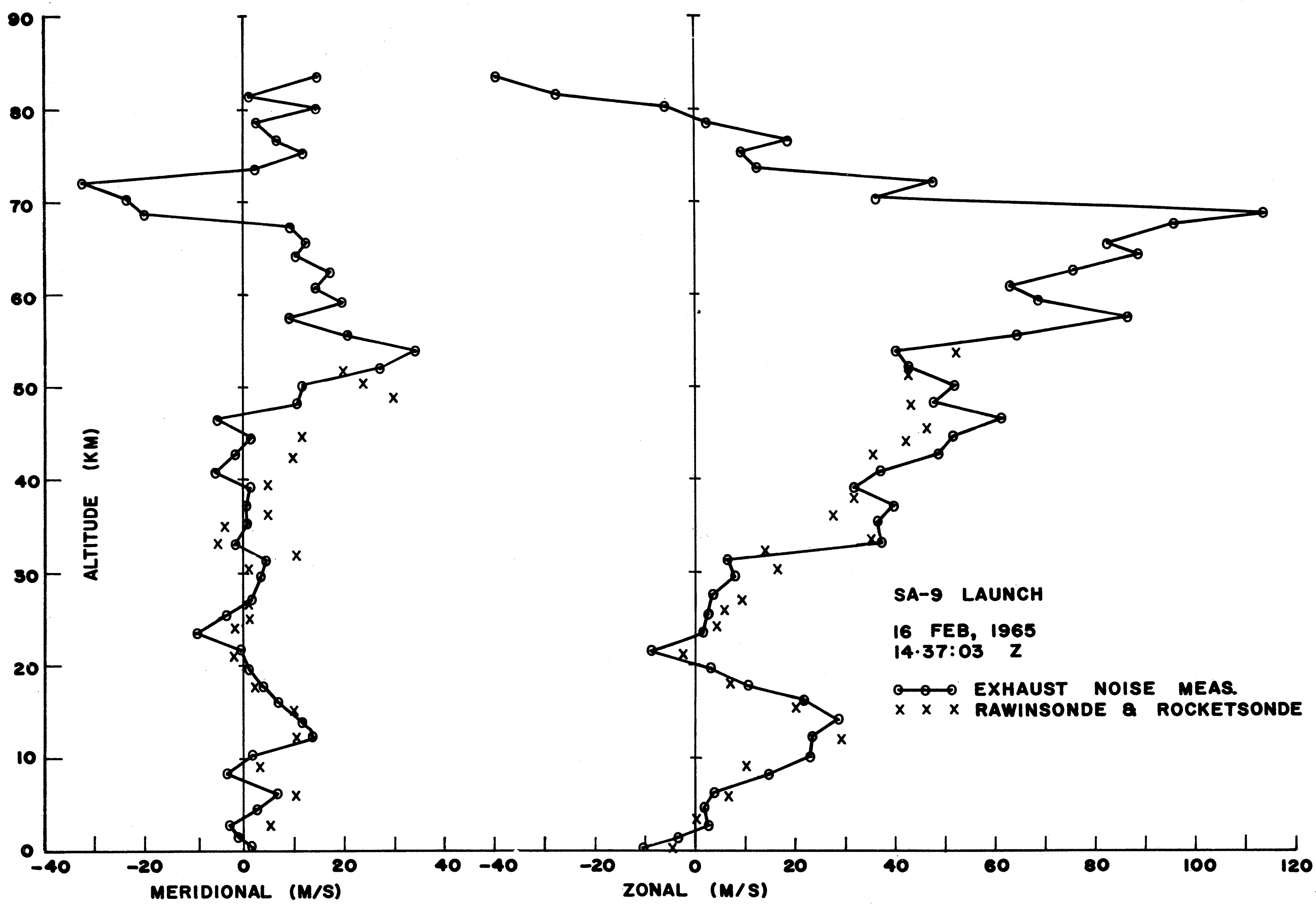

FIG.-1 SA-9 WIND PROFILE

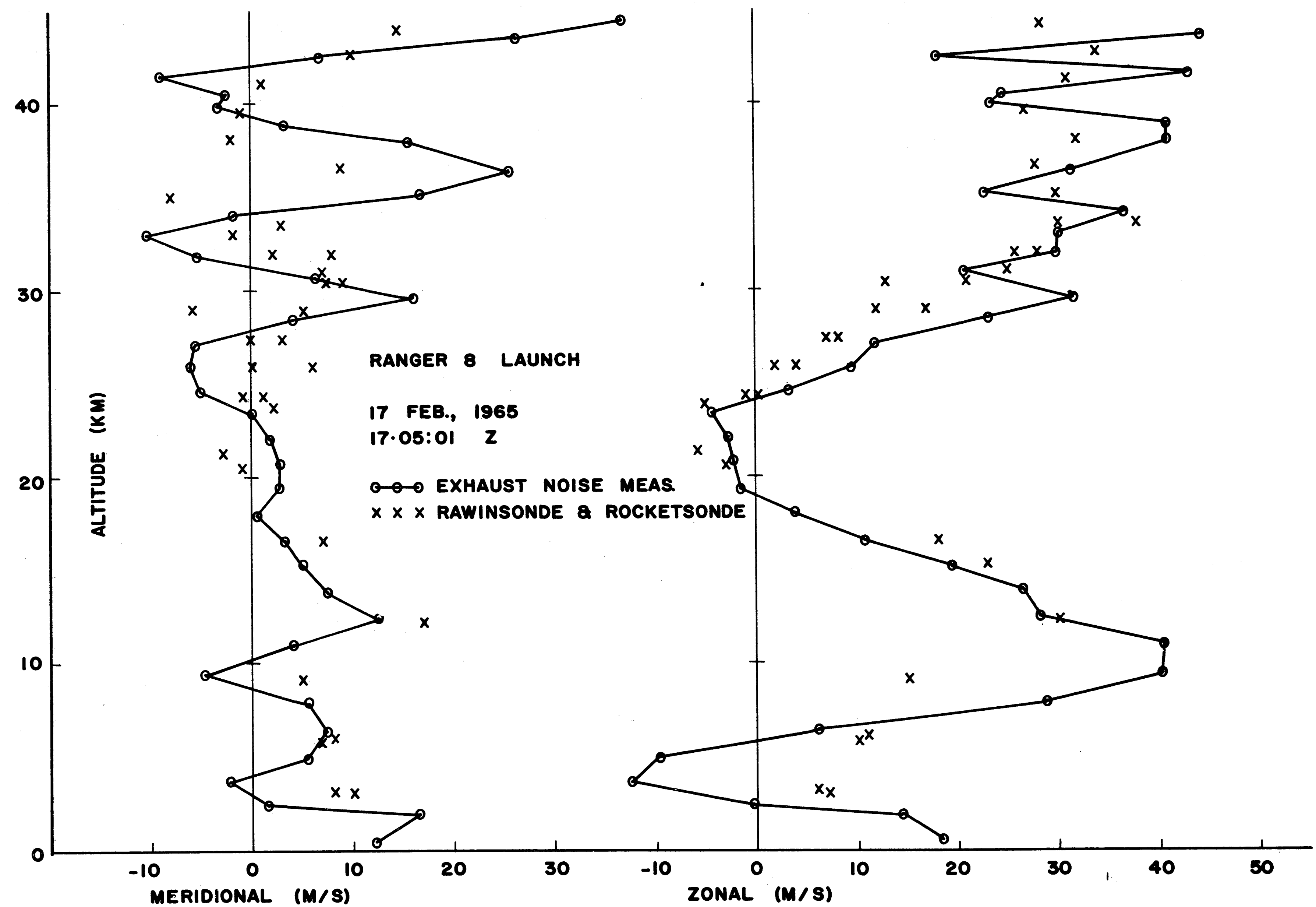

FIG. 2 RANGER 8 WIND PROFILE

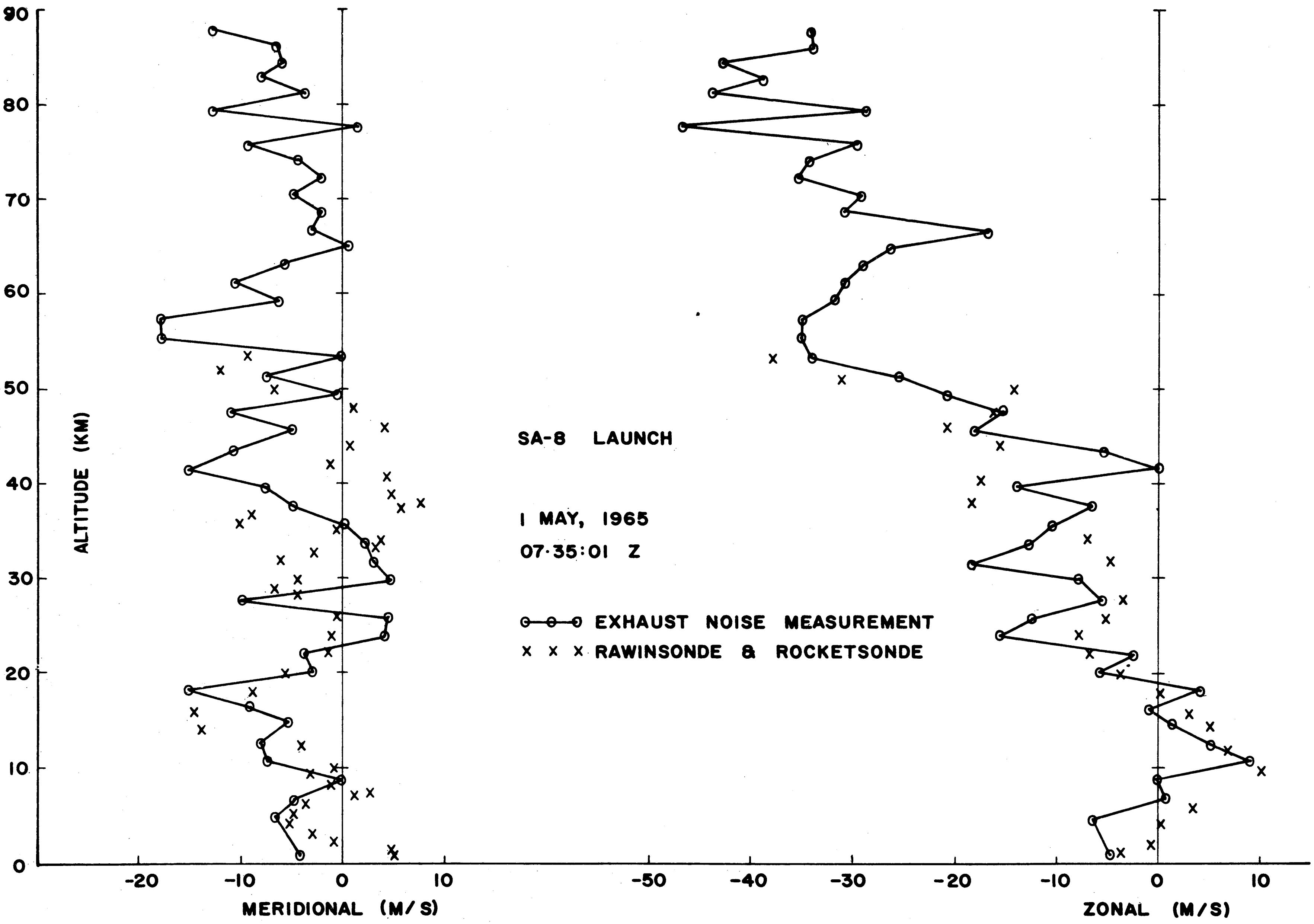

FIG. 3 SA-8 WIND PROFILE

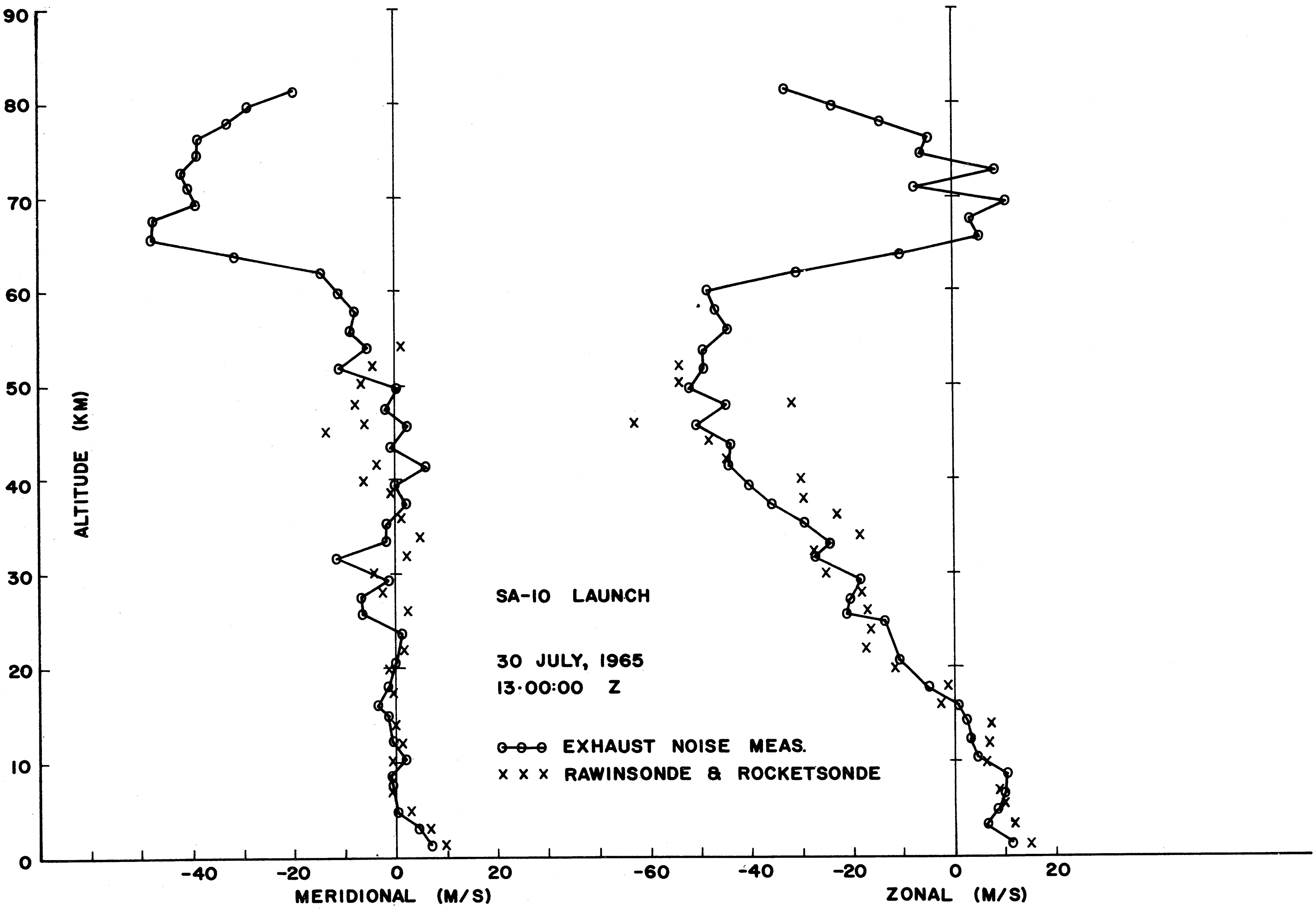

FIG. 4 SA-10 WIND PROFILE

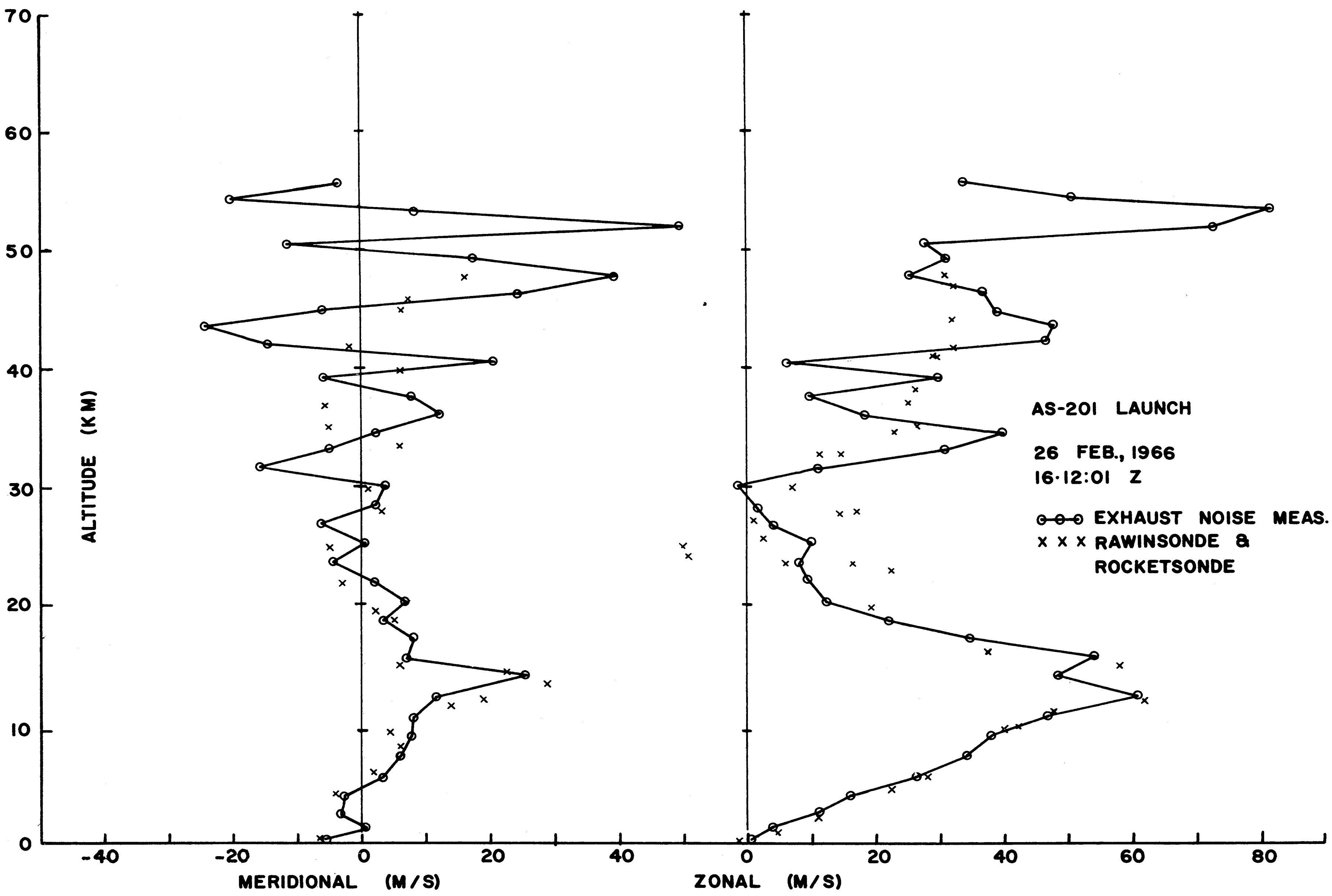

FIG. 5 AS-201 WIND PROFILE

meaningful interpretation of data.

DATA ANALYSIS

Introduction

A significant improvement in speed and accuracy of data analysis has been made possible by the use of an automatic cross correlation program. Before this development, the microphone time differences were read manually from oscillographs, necessitating a tedious pattern searching and measuring procedure of the microphone outputs. Briefly, the new method is to use a computer to digitize the data and calculate the digital equivalent of the following function.

$$R(t') = N \int_{Slice} \psi^{1}(t)\, \psi^{2}(t + t')\, dt \qquad (1)$$

where: R is the magnitude of the cross correlation function

t' is a variable time difference parameter

N is a normalization factor

ψ^1 and ψ^2 are the two time dependent microphone outputs

Slice is a pre-set integration time interval

A typical plot of R(t') is shown in Fig. 6. The computer varies the parameter t' and calculates R for each value. The t' corresponding to the principal maximum of R is the required time difference between the two microphones. This procedure

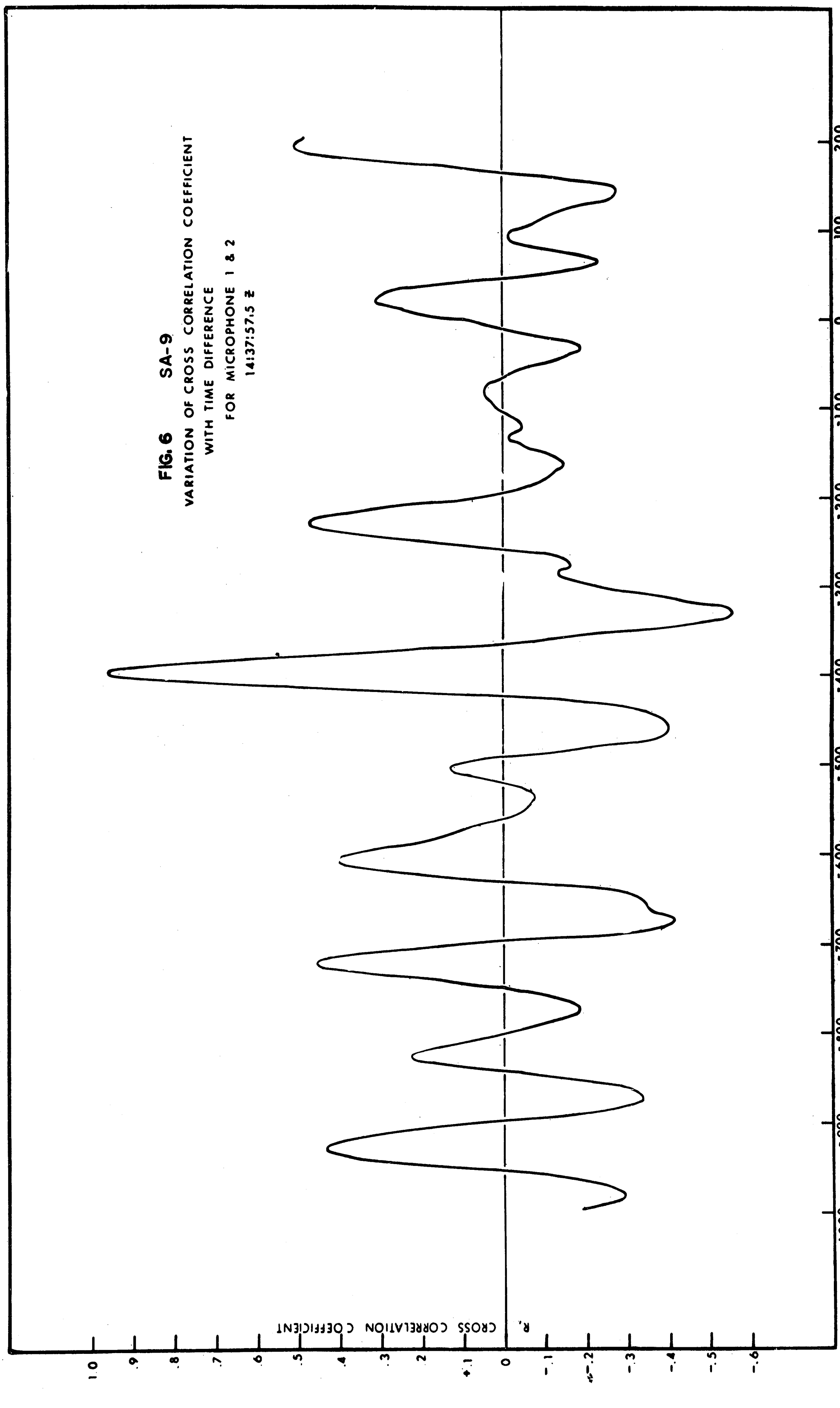

FIG. 6 SA-9
VARIATION OF CROSS CORRELATION COEFFICIENT
WITH TIME DIFFERENCE
FOR MICROPHONE 1 & 2
14:37:57.5 Z

is repeated for each microphone paired with microphone No. 1. These data are then smoothed and inputed to the IBM 7090 computer for wind profiles.

Discussion

The first step in the data reduction is the digitization of the recorded microphone outputs and range timing onto magnetic tape in a format suitable for computer processing. The computer being used is a Digital Equipment Corp. PDP-8 which has a core storage capacity of 4000 12 bit words and a cycle time of 1.5 μ sec. The sampling rate is 1000 per sec. for each data channel. This high rate avoids the necessity of interpolating R after the computation and also results in a higher confidence level.

The cross correlation computation utilizes the following formula which is equivalent to the analog formula No. 1.

$$R = \frac{\sum xy - \frac{\sum x \sum y}{N}}{\left\{\left(\sum x^2 - \frac{(\sum x)^2}{N}\right)\left(\sum y^2 - \frac{(\sum y)^2}{N}\right)\right\}^{1/2}} \qquad (2)$$

where x and y represent samples from the two channels and N is the number of sample pairs. The slice chosen is usually 0.5 sec or 500 samples pairs. It should be noted that the computation always uses 500 sample pairs, even when the time difference t' exceeds the slice interval. In some cross correlation programs the time difference parameter is limited to be less than some fraction of the slice, usually 1/5. In these programs only data within the slice is considered, so as t' is increased the number of sample pairs and confidence level decrease.

Fig. 7 shows a typical section of microphone output record. This particular record of microphones 1, 2 and 3, was made at T + 57 sec during the launch of Saturn SA-9. The cross correlation is visually evident and indicated by the arrows. To illustrate the technique, the automatic cross correlation was applied to microphone pair 2-1 for the 0.5 sec slice shown enclosed on microphone No. 1. Fig. 6 shows the resulting variation of R(t'). The principal maximum occurs at a delay of 0.4 seconds which is in agreement with the visual correlation.

To speed the cross correlation computation during an actual data run some additional information is inputed, in the form of periodic rough estimates of expected time differences. These estimates are in turn based upon estimates of the sound source position as a function of range time. The time differences are then computed, in a first pass, to within ±20 ms at 10 sec intervals of range time. These data are then used in a second pass to compute time differences to ±1 ms accuracy at 0.5 sec intervals of range time. An obvious method of avoiding the necessity of the estimates and dual computations would be to program the computer to search as much as necessary for the first correlation and then to calculate the remaining correlations by continually up-dating itself on the basis of prior results. However, implementing this technique would require more core storage

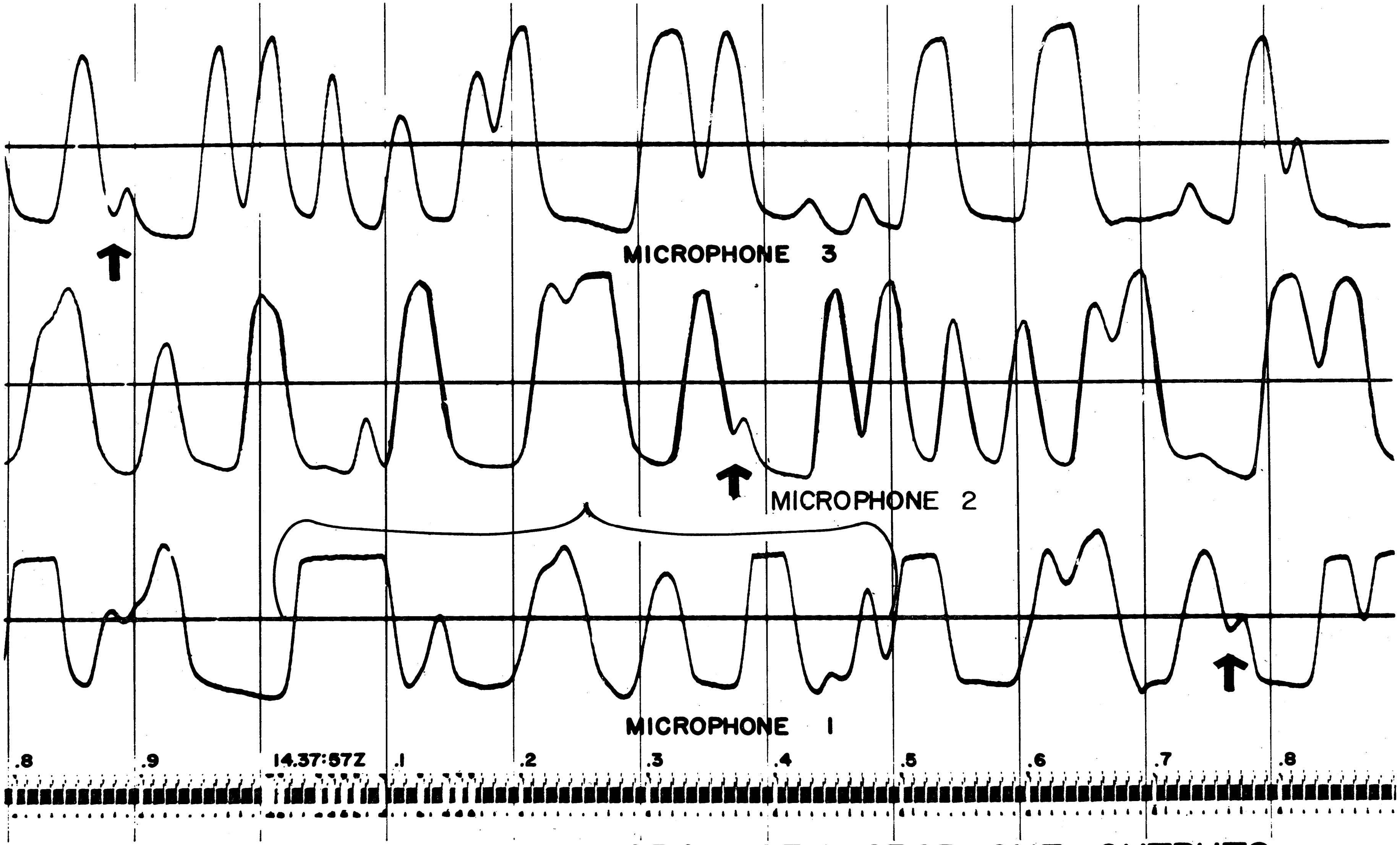

FIG. 7 TYPICAL OSCILLOGRAM OF MICROPHONE OUTPUTS

than is available on the PDP-8 since the present program uses nearly all this storage capacity.

The total computer time required for the cross correlation for one flight, including two passes on 8 microphone pairs over 400 sec of range time is presently about 20 hours. Using the up-dating procedure described above this time could easily be cut in half. This time requirement is extremely variable since it depends on several parameters. For example, by digitizing at 500 cps rate and evaluating R at 1 sec. intervals, the total time could be reduced to 5 hours.

Fig. 8 is a plot of the time difference between each microphone and microphone No. 1 as a function of range time. Since a cross correlation is computed each 0.5 sec. the points are relatively dense. This data is smoothed and inputed at 10 sec intervals of range time for wind profile calculations on the IBM 7090 computer. Occassionally a microphone will not yield a good correlation during a particular slice. These occurrances are usually due to switching transients, background noise or wind interference. When a cross correlation coefficient is less than 0.7 it is not plotted or used in the data reduction. The wind profiles of Fig. 1 are the result of ray tracing the smoothed data at T $\pm$ 50 sec., 60 sec... 420 secs.

As can be seen from Fig. 8 the scatter in the time differences increases with range time. The reasons for the scatter are not yet understood, however, the following possibilities are offered.

1. Anomalous Propagation

Anomalous propagation paths could cause sounds generated by the exhaust at different points along the trajectory to arrive simultaneously and from different directions at the microphone array. These sounds, mixing in some complicated way with the direct signal, might give a directional variability to the arrival angle and a corresponding variability in the time differences resembling the observed scatter. There is, however, at least one weakness in this argument. If the sound arrival angle is affected via this mechanism, one would expect a measure of this variability, such as the mean square deviation, to be proportional to the distance along one axis of the microphone from the center of the array. That this is not the case can easily be seen by comparing the time differences from pairs 2-3, 4-5, 6-7, and 8-9. Also, one would expect the scatter to correlate along each leg of the array, and this is not generally observed except occassionally when the output signal of microphone No. 1 is degraded to the extent that R is too low to be plotted in which case the perturbation is evident on all the time differences.

So at best, this explanation is questionable.

2. Local Interference Effects

Wind and background noise may combine with the desired signal to distort its wave shape. These distortions could cause scatter in the time differences dependent on the signal to noise ratio and would be expected to reduce the value of the cross correlation coefficient. It is observed that the cross correlation coefficient generally decreases slightly with increasing range time, probably because of the decreasing S/N ratio. However, it remains difficult to accept this explanation as the sole cause of the scatter because of the extremely high values of R, typically greater than 0.9. In fact, scatter is occassionally observed in a continuous series of intervals all of which yield correlation coefficients greater than 0.95. Therefore, it seems the interference effect can be at most only partially responsible for the scatter.

3. Frequency of Data

Another effect which may partly explain the scatter is the frequency of the data. The exhaust noise as recorded from the hot wire microphones seems to be predominantly about 8 cps; and the rate of variation of the cross correlation coefficient is dependent on this frequency. This variation might be sufficiently slow so that perturbations on the curve caused by slight interference would displace the principal maximum substantially. It should be noted that in addition to decreasing S/N ratio, the predominant frequencies of the data have been observed to decrease with increasing range. This is to be expected by considering atmospheric filtering. The scatter resulting from this effect could be reduced by selectively monitoring the higher frequencies of the exhaust noise. To investigate this possibility capacitor microphones with higher frequency response are being constructed.

Until the mechanism causing the scatter is understood and the necessary corrections made, it seems expedient to make use of the data as is. Since much more data is cross correlated than is used as input for wind profiles, smoothing is used to significantly reduce the magnitude of the expected error in time differences. The angle of arrival errors are reduced further with the redundancy provided by the number of microphones. Nevertheless, the over all accuracy of the experiment is limited by the scatter. The contributions of other factors which have been investigated i.e. trajectory error, speed of sound error etc. are small compared to the errors caused by this uncertainty.

CAPACITOR MICROPHONES

As noted earlier, it is hoped that the scatter in time differences can be reduced by the use of higher frequency microphones. To test this possibility, four capacitor microphones borrowed from a University of Michigan acoustical laboratory are being re-built for this experiment. The tentative electronic circuits of the microphones are shown in Fig. 9. The microphones frequency response characteristics can be changed by adjustment of R_1, R_2, C_1 and the feedback networks. The sensitivity can be remotely controlled by selecting one of two feedback networks with the relay.

Since the object of these microphone is to utilize the higher frequencies, (the hot wire microphones are tuned to about 6 cps) the response is adjusted as shown in Fig. 10. Final adjustment of the microphone sensitivity will be determined by experiment so the response is shown on a relative scale.

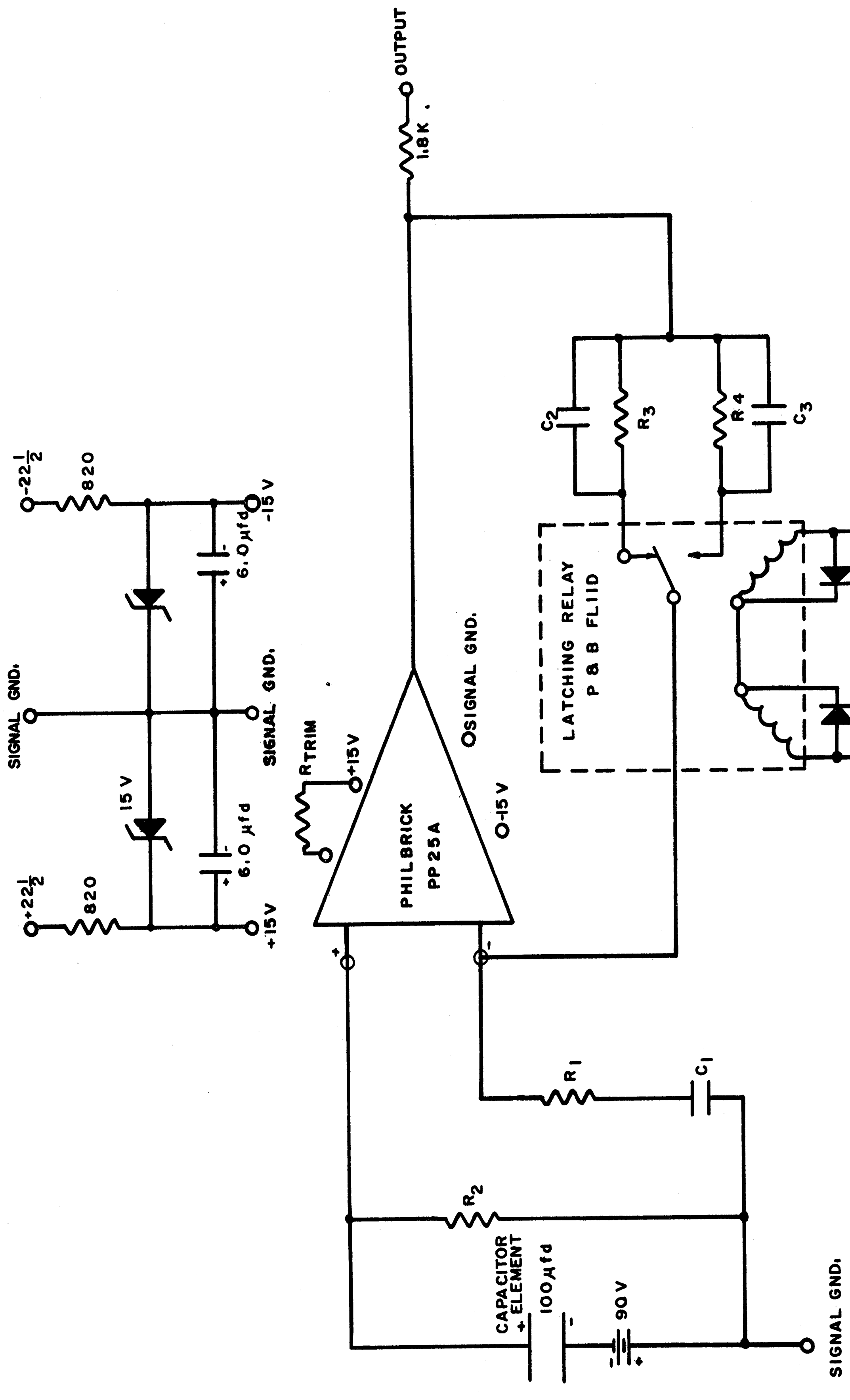

FIG.9

CAPACITOR MICROPHONE RELAY SCHEMATIC

CONCLUSIONS

During the last half of the contract period, the research reported here will be continued. In addition to the acoustical measurements and data reduction of the Saturns, effort will be concentrated on the time difference scatter problem, since it is the main contributor to wind profile errors.

The automatic cross correlation technique can be used to calculate the magnitude of the expected errors. The error analysis presented in July 1965* is based on assumptions of the time difference errors. Since these errors can now be calculated a more rigorous error analysis is planned.

*Bushman, W. W., Kakli, G. M., Carignan, G. R., "An Acoustic Wind Measuring Technique," Univ. of Mich Tech. Report 05911-2-T, Contract NAS8-11054, July 1965.