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A STUDY OF THE APPLICATION OF MICROWAVE TECHNIQUES TO THE MEASUREMENT OF SOLID PROPELLANT BURNING RATES

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by

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I. INTRODUCTION

The Utilization of Doppler microwave techniques for the measurement of solid propellant burning rates has been successfully demonstrated under the subject grant.* Both high aluminum content propellants (TPH 8009) and low aluminum content propellants (BF-117) were used in the investigation.

The measurement was accomplished by determination of the phase angle between microwaves incident upon the burning surface and the microwaves reflected from the burning surface back through the unburned propellant. Precise measurement of the phase angle requires a distortion-free Doppler signal which is independent of the amplitude of the microwave signals. Considerable distortion and effects of amplitude were present in all tests conducted.

Accordingly, a full-bridge microwave interferometer was designed, purchased, and tested in 91 rocket firings. This report covers the characteristics of the complete interferometric system, with emphasis on the operational techniques involved.

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* Wood, H. L. and O'Brien, W. F.; "A Study of the Application of Microwave Techniques to the Measurement of Solid Propellant Burning Rates," NASA CR-66627, April, 1968.

II. DESCRIPTION OF THE MICROWAVE SYSTEM

The microwave system described in the following section is a full-bridge interferometer, capable of operating at power levels up to 140 milliwatts and over a frequency range of 37.8 to 40.0 GHz. The system was designed by the principal investigator, in consultation with microwave engineers of TRG, Inc. (a subsidiary of Control Data Corporation), and was fabricated by TRG, Inc.

Figure 1 is a photograph of the microwave interferometer. Supporting instrumentation is not shown. Figures 2 and 3 are schematic diagrams showing components of the system and the method of signal processing. Figures 2 and 3 will be used to describe the operating principle of the interferometer. A complete list of components is presented in the Appendix.

Operating Principle of the Interferometer

Referring to Figure 2, microwaves are generated in the klystron which is mounted in air oil bath for temperature stability. The microwaves are transmitted through waveguide past a ferrite isolator which prevents the return of any reflected microwave energy into the klystron.. A variable attenuator is next provided for power level adjustment. The microwaves then pass through a directional coupler wherein one-tenth of the microwave energy is directed through a resonant cavity frequency meter into a thermistor mount for power measurement.

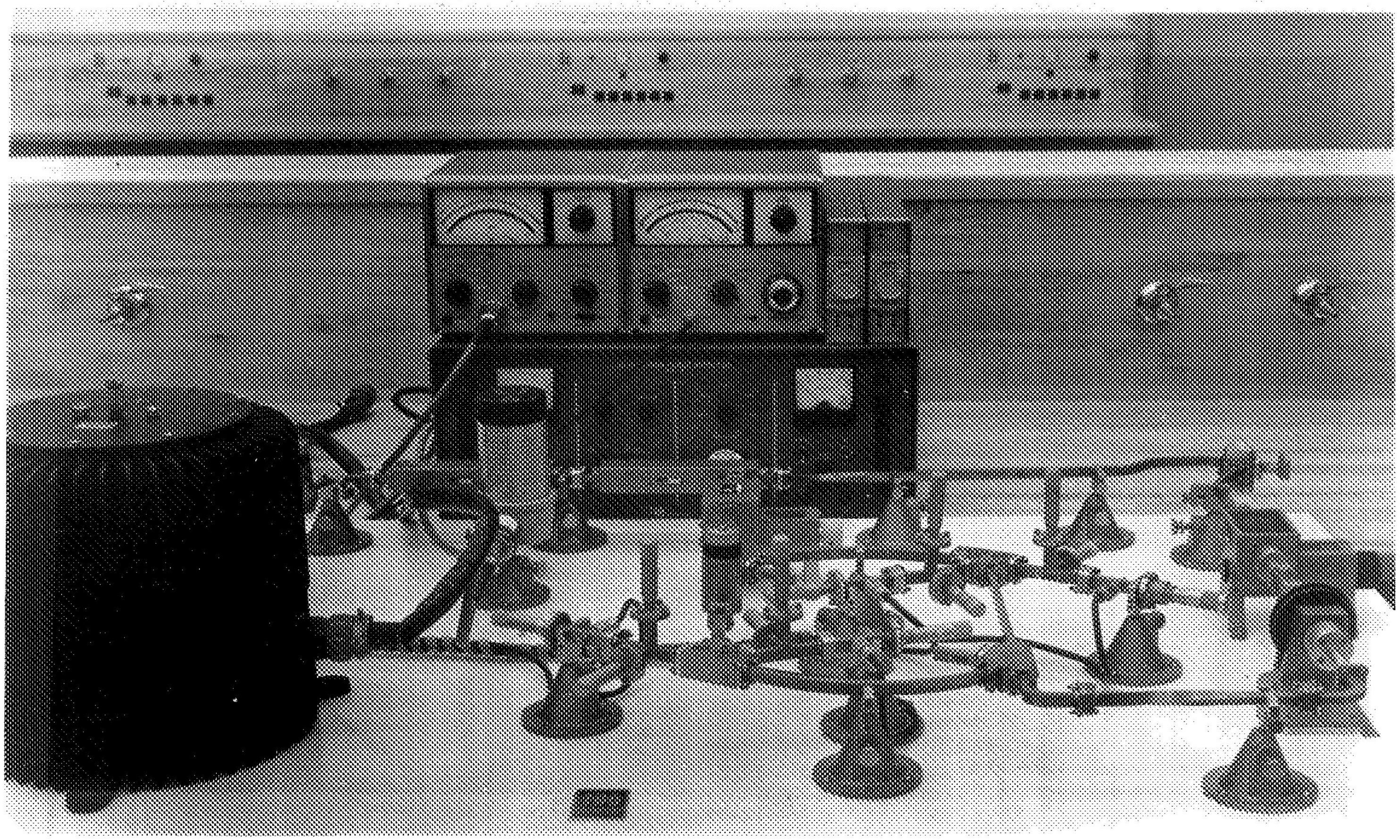

Figure 1. The Microwave Interferometer

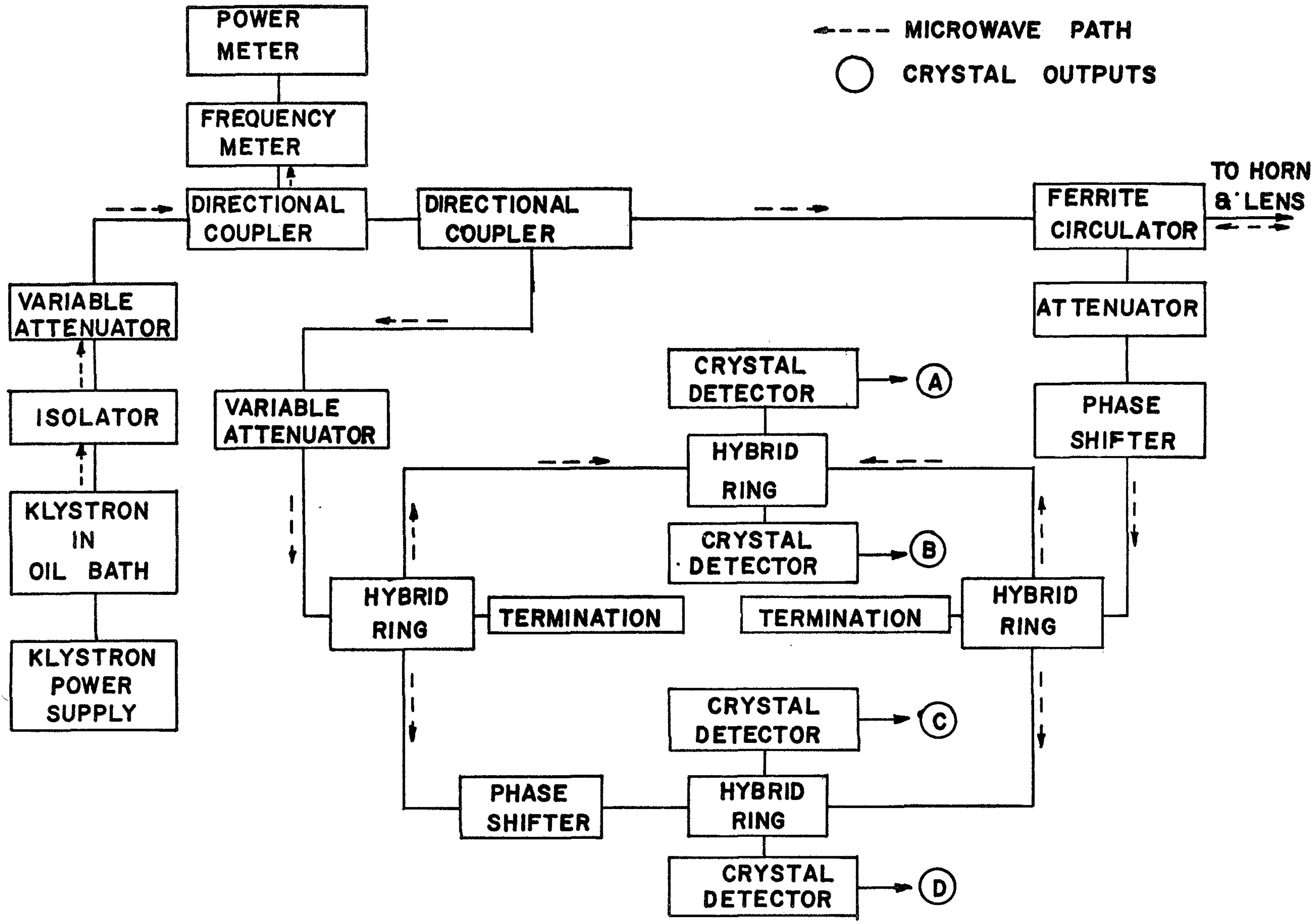

Figure 2. Schematic Diagram of the Microwave Interferometer

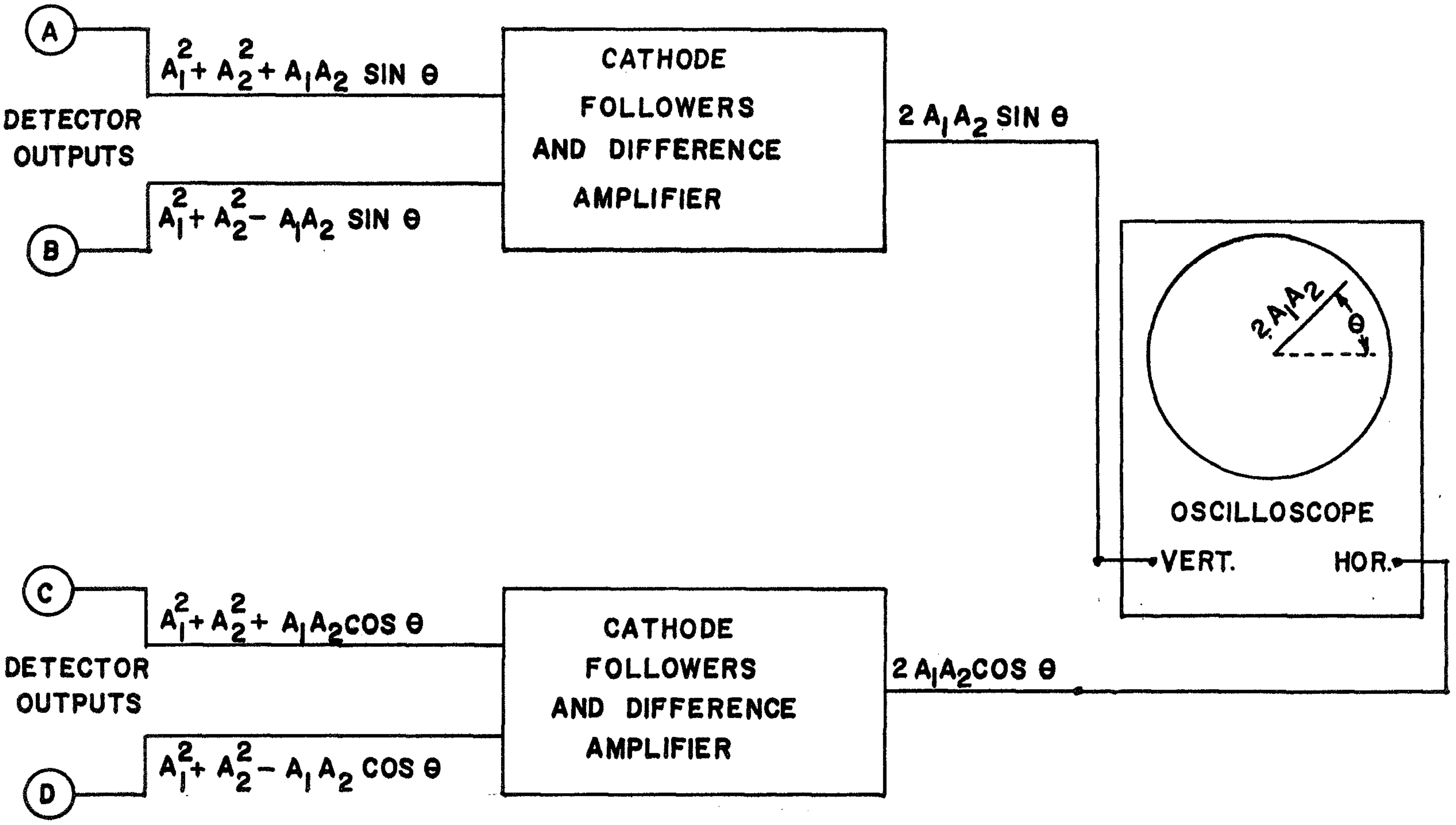

Figure 3. Schematic Diagram of Signal Processing

The microwaves then pass into a second directional coupler wherein another portion of microwave energy, for a reference signal, is diverted, through an attenuator for reference level adjustment, into the left-hand side of the bridge proper. The reference signal is then equally divided by a hybrid ring, one half passing into the upper section of the bridge and appearing an another hybrid ring. The other half of the reference signal passes through a 90° phase shifter into the lower section of the bridge and appears at a third hybrid ring.

Meanwhile, the main microwave signal passes from the second directional coupler through a ferrite circulator to the antenna located in the rocket motor. The antenna, a horn-lens combination or a horn alone, transmits the microwaves through the unburned propellant to the burning surface. A portion of the microwaves are reflected from the burning surface, received by the antenna, and returned to the circulator. The circulator prevents the return of the reflected microwaves toward the directional couplers (and klystron) and directs them, via an attenuator and a precision phase shifter, to the hybrid ring at the right hand side of the bridge. The hybrid ring equally divides the reflected microwaves, one half passing into the upper section of the bridge and the other half into the lower section of the bridge.

In the upper and lower hybrid rings the reference microwaves and the microwaves reflected from the burning surface are mixed, their sum appearing in one output arm of a ring (at detectors A and C) and their difference in the other output arm of a ring (at detectors B and D). If the amplitude of the reference microwave signal is denoted by A_1, the amplitude of the reflected microwave signal by A_2, and the phase angle between the reference and the reflected microwave signals by θ, the outputs of the square-law crystal detectors will be as shown in Figure 3.

By use of differential amplifiers, two signals are derived, one proportional to Cos θ and the other proportional to Sin θ. The two signals are applied to the horizontal and vertical axes of an oscilloscope as shown. If the microwave signal is modulated with a high frequency square wave, a radial display will be produced on the oscilloscope. The angular position of the radius vector is the phase angle between the reference and reflected signals. If the reference signal, A_1, is maintained constant, the length of the vector is proportional to the magnitude of the reflected signal. It should be observed here that the radius vector could not be clearly obtained on the screen of the oscilloscope. This will be discussed in a subsequent section.

As burning of the propellant occurs, the phase angle between the reference (or incident) microwaves and the reflected signal will change with time. The radius vector on the oscilloscope screen will rotate, making one revolution for each half-wavelength of propellant consumed. From the angular velocity of the radius vector, the burning rate of the propellant can be deduced:

$$r_b = \frac{\lambda\omega}{2}$$

Where: r_b = Burning rate, in/sec

λ = Wavelength of microwaves in the propellant, in.

ω = Angular velocity of radius vector, rps

Detailed Procedure for Use of the Interferometer

The following sections are intended as a guide for actual use of the interferometer. It should be observed that some procedures may necessarily have to be determined by trial and error, dependent upon the propellant utilized and the configuration of the propellant grain. Typical operating values will be presented for TPH 8009 propellant grains approximately 2.5 inches in diameter and 2 inches in length, fully restricted on the cylindrical surface and one end. The procedure applies only to the interferometer employed in the subject investigation.

Klystron Operation

The klystron is powered from its own separate supply. It is placed in operation by first applying rated filament voltage, with beam voltage at zero, grid voltage at its maximum negative value, and repeller voltage at a value previously established for the frequency at which the klystron is to operate (generally supplied by the klystron manufacturer). Following closure of protective relays (approximately one minute) in the klystron power supply (as evidenced audibly) the beam voltage is slowly raised to rated value. Grid voltage is then slowly made less negative while beam current is observed. A sudden increase in beam current indicates that the klystron is in operation. The power level is then adjusted by further change in grid voltage, taking care not to exceed rated beam current. Power level meter readings must be multiplied by 10 because of the particular directional coupler employed.

Frequency of operation can be determined by adjustment of the resonant-cavity frequency meter until a drop in power of approximately 1 db is observed. The frequency meter is then in resonance and frequency can be read directly from its scale. The frequency of the klystron can be adjusted by mechanically changing the klystron cavity. An adjustment knob on the side of the oil bath is provided for such. If the frequency is changed, the repeller voltage should be adjusted in order to keep the klystron in oscillation. Frequency changes should be made at relatively low power.

The particular klystron in use will not operate stably at power levels less than approximately 25 milliwatts. Thus, it is advisable to operate at a higher power level and use the output attenuator if less than 25 milliwatts is desired.

Typical operating conditions for the 40V10, OKI Electronics, klystron are:

Heater voltage: 6.3 volts
Repeller voltage: -240 volts
Beam voltage: 2400 volts
Grid voltage: -138 volts
Beam current: 23 milliamperes
Power: 135 milliwatts
Frequency: 39.85 GHz

Crystal Detector Adjustment

The objective of crystal detector adjustment is to obtain equal outputs, in phase, from each pair of detectors when they are exposed to the same microwave signal.

With the klystron operating at the desired power level and frequency, the attenuator leading to the reference side of the bridge is set at zero attenuation and the attenuator in the reflected signal side of the bridge is set at maximum attenuation (50 db). The phase shifter in the lower side of the bridge is set at approximately 90°. In this manner, all four crystal detectors are exposed only to the reference microwave signal.

With the internal 1000 Hz square-wave modulator of the klystron power supply in operation, a single crystal detector is connected to a standing wave meter and its output observed. The output of the detector is first maximized by successive adjustment of its E-H tuner and sliding short. If the crystal output is low (as compared to the other three), it may be necessary to rotate and/or slide the crystal in its mount to obtain adequate output. The foregoing is repeated for each detector. The output of the detectors should be within approximately 2 db of each other.

With all detectors maximized, attenuators provided in the output cables of each detector are adjusted until the detector outputs are equal. The detectors are then connected, in pairs, as shown in Figures 2 and 3, to the differential amplifiers. With the klystron operating in the continuous wave mode, the output of each amplifier should be zero. If not, fine adjustment of the attenuators in the detector cables is required.

Initializing the System

Before the system can be initialized, it is necessary to prepare the test rocket motor for firing with the horn or horn-lens antenna mounted in it and connected by waveguide to the interferometer.

The attenuator at the reference side of the bridge is set to approximately 5 db, a value determined experimentally for a 2 inch thickness of TPH 8009 propellant. This setting can be estimated for other propellants and thicknesses by moving a sheet of metal near the surface of a test propellant slab positioned against the antenna. The reference signal level is then adjusted until a maximum signal variation is obtained. The attenuator should then be set to slightly lesser value for actual operation since total reflection from the burning surface does not occur. The reference signal should be approximately equal to the reflected signal for optimum results.

The attenuator at the reflected signal side of the bridge is set at 0 db. The magnitude of the reflected signal is, in general, quite small and should not be attenuated.

With the outputs of the two differential amplifiers (set for equal gain) connected to the two axes of an oscilloscope, the precision phase shifter in the reflected signal side of the bridge is rotated rapidly by hand. The resultant display on the oscilloscope should be a perfect circle, centered at electrical ground. If the display is an ellipse with its axes not corresponding to the oscilloscope axes, the phase shifter in the reference arm of the bridge must be adjusted. If the display is an ellipse with axes coinciding with those of the oscilloscope, the relative gain of the differential amplifiers should be adjusted. If the circle is not centered about electrical ground, the crystal detectors must be readjusted.

As a final check, the precision phase shifter is rotated through 90° increments on its calibrated scale. This should result in a shift of the oscilloscope display in four 90° increments. If not, the procedure above should be repeated.

It should be observed that detector adjustment and initialization of the system are very sensitive to microwave power level, and care must be taken to maintain exactly the same power level throughout.

In the foregoing procedure, the reflected signal is primarily the signal reflected from fixed surfaces within the rocket motor. To eliminate these fixed reflections a sliding screw tuner (or E-H tuner), located in the waveguide between the interferometer and the antenna, is employed. While rotating the precision phase shifter by hand, the tuner is adjusted such that the radius of the circle displayed on the oscilloscope is reduced to zero. In this manner, the reflections from fixed surfaces are reduced to zero. The system is then properly initialized and ready for operation.

Peripheral Instrumentation and Data Readout

To conduct a test, the ouputs of the two differential amplifiers are connected through a servo-driven variable gain device to a magnetic tape recorder as described in NASA CR-66627. The two microwave signals are recorded throughout the test firing, along with other desired information.

To read out burning rate data, the two microwave channels on the recorder are connected to the two axes of an oscilloscope. The recorder is then run in the reproduce mode at reduced speed. A circular display is produced on the oscilloscope screen. With the display carefully centered on the oscilloscope, the screen of the oscilloscope is covered with opaque masks, leaving only a thin slit open across the x-axis. A photo-diode and appropriate circuitry is positioned in a darkened enclosure such that it can detect the passage of the electron beam across the slit. The output of the photo-diode is connected to a recording oscillograph.

When the tape is played, a series of pulses is recorded by the oscillograph. Each pulse corresponds to a regression of the burning surface by one-fourth of a wavelength of the microwaves in the propellant. From the time between pulses, the average burning rate over one-fourth wave length of propellant, at the corresponding time increments can be calculated.

Typical recordings are presented in the following section.

III. EXPERIMENTAL PROGRAM

A total of 91 firings were conducted with the interferometer and the test rocket motor described in NASA CR-66627, using TPH-8009 propellant. The tests had three major objectives:

1. To establish referencing and initializing procedures for the interferometer,
2. To evaluate the effect of microwave power level on signal quality, and
3. To evaluate the characteristics of different horn designs.

The first objective was achieved following 52 rocket firings. During these tests, the procedures for use of the interferometer presented in the preceding section were developed. The tests were mainly qualitative and in many instances no data was obtained. Such tests were necessary inasmuch as no information was available on the subject application of a microwave interferometer.

Having obtained a reliable operating technique, attention was directed to the effect of power level on signal purity. A series of tests was conducted in which the power level was varied from 15 to 120 milliwatts. Signal to noise ratio was found to be best at a power level of 45 milliwatts. During these tests, repeated efforts were made to eliminate the starting transient appearing in the microwave signals. The source of the transient could not be established and it could not be eliminated.

In the last series of tests, three different horns were used: a commercial 20 db pyramidal horn, a conical horn with 10° half-angle, and the horn-lens combination described in NASA CR-66627. All three horns had essentially the same aperture.

The tests were conducted at three different power levels: 15, 25, and 45 milliwatts. The horn-lens combination and the 10° conical horn produced microwave signals of comparable good quality. The 20 db pyramidal horn produced inferior signals and was abandoned.

Concial horns with half-angles of 15° and 20° were also manufactured but were not used in rocket firings following results of a side experiment in which the beam diameter of microwaves in propellant was measured by use of liquid crystals. In this experiment a mixture of Edmund Scientific VL-401-R and VL-401-L liquid crystals were painted on one side of a small slab of propellant. The horn being tested was positioned on the opposite side of the propellant. Microwave energy absorbed by the propellant caused slight temperature changes of the propellant with a resultant change in color of the liquid crystals. A change in temperature of 2°C caused a complete change of color from red to blue. Comparison of the yellow spot size produced yielded a relative measure of beam diameter. The 10° conical horn and the horn-lens combination both exhibited a beam diameter of approximately 0.5 inches through one-half inch of propellant. The 15° conical horn had a beam diameter of 0.7 inches and the 20° horn a beam diameter of 0.85 inches. Tests were limited to a propellant thickness of one-half inch by microwave power available.

Typical Test Results

As previously mentioned, the tests conducted were mainly qualitative inasmuch as the validity of the microwave technique had already been proven quantitatively. Thus, only a typical set of test results is presented. All test data is retained on magnetic tape by the investigator.

Shown in Figure 4 are recordings of the two microwave signals and the rocket motor chamber history. Figure 5 presents a time-expanded portion of the microwave signals and the quarter-wavelength pulses derived from the oscilloscope display. Test conditions are given below.

Firing Number: 87A
Date: August 26, 1969
Antenna: Horn-lens combination
Power Level: 45 milliwatts
Frequency: 39.86 GHz
Reference Attenuator Setting: 5db
Propellant: TPH 8009, 2" thickness

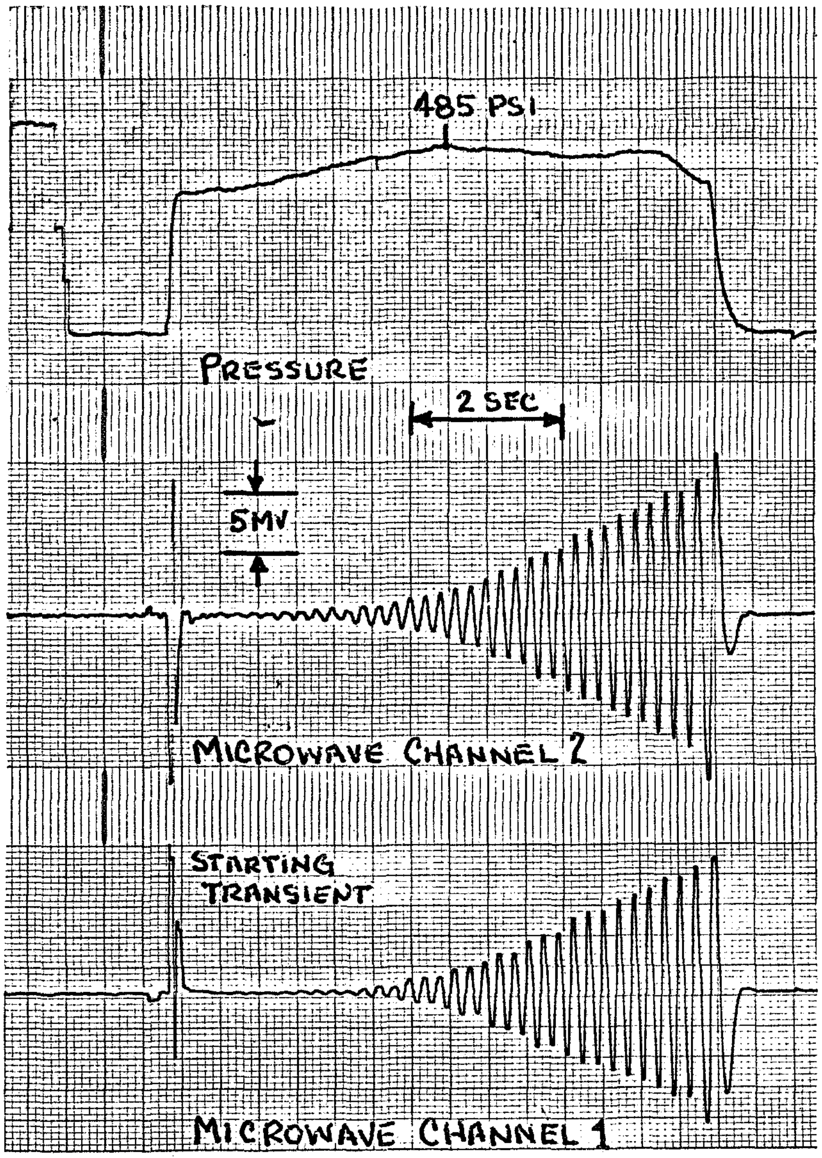

Figure 4. Typical Microwave and Pressure Recordings (Firing 87A).

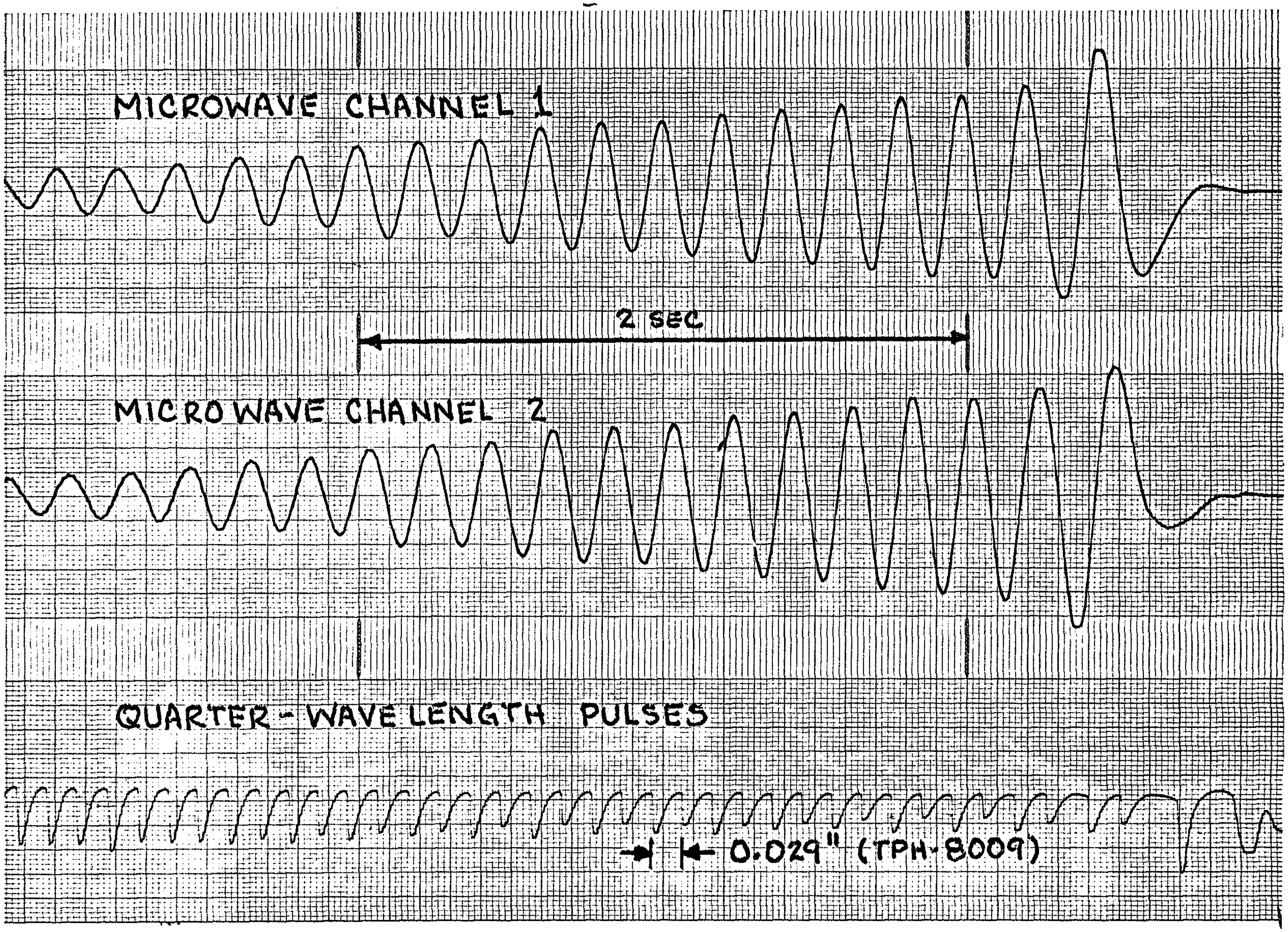

Figure 5. Microwave and Quarter-Wavelength Recordings -

Expanded Time Scale (Firing 87A)

IV. DISCUSSION

The major objective of the research covered by this report was to obtain high purity microwave signals from which burning rate information could be derived. As evidenced by the recordings presented in Figure 5, such was accomplished.

Amplitude effects were eliminated by use of the interferometer and proper manipulation of the four microwave signals detected. Proper tuning removed unwanted microwave reflections from fixed surfaces which would contribute to an error in the rate of change of phase angle and, consequently, in burning rate.

Use of either the horn-lens combination or the 10° concial horn produced high quality signals but the 20 db pyramidal horn introduced signal distortion. Distortion with the pyramidal horn is attributed to the larger area of the burning surface illuminated by the microwaves. If the burning surface regressed at a slight angle off normal to the motor axis, the larger area illuminated would have a pronounced effect.

The higher operating frequency, 40 GHz, a compared to that of previous tests, improved resolution of the position of the burning surface. At 40 GHz the quarter-wavelength is propellant is 0.029 inches, while at 30 GHz it is 0.038 inches. Quarter-wavelength measurements from recordings can easily be accomplished.

It had been anticipated that a rotating vector display could be obtained on an oscilloscope and that, by photographing the display, much better resolution, even for transients, could be obtained. The combined characteristics of the 1000 Hz square-wave modulator, the klystron power supply, and the klystron introduced distortion into the 1000 Hz modulated microwave signals with resultant severe distortion of the radial vector. The mask and photodiode arrangement was an attempt to overcome this difficulty. An attempt was made to utilize two slits in the mask such that one-eighth wavelength measurements could be made, but allignment of the oscilloscope trace became virtually impossible.

Another approach to reduction of data was an attempt to compute the frequency of the Doppler microwave signal directly from one of the microwave recordings. Lack of adequate digitizing equipment and difficulties encountered in programming made this impossible.

It is felt that transient burning measurements can be made by the interferometer if the proper data reduction techniques can be developed.

It had also been anticipated that the higher power available from the 40V10 klystron would permit measurements on propellant grains greater than two inches in thickness. However, the dynamic range of the microwave signals (in excess of 300:1) and the lower signal-to-noise ratio at higher power precluded such. With the instrumentation available it was not possible to make measurements on grains greater than two inches in thickness. It is felt that with improved electronic instrumentation, with large dynamic operating ranges, measurements can be made on grains of greater thickness.

V. CONCLUSIONS

As a result of the subject investigation the following conclusions are drawn:

1. The microwave interferometer developed produces high purity Doppler signals from which burning rate information can be derived.
2. Transient burning rate measurements cannot be currently made with the interferometer, but the position of the burning surface can be located within 0.029 inches with relative ease.
3. Either the horn-lens combination or the 10° half-angle conical horn are suitable transducers for microwave burning rate measurements.

VI. RECOMMENDATIONS

It is recommended that attention be directed to improvement of data reduction techniques with the objective of obtaining transient burning rate information from the microwave interferometer.

VII. ACKNOWLEDGEMENTS

Sincere appreciation is expressed to the National Aeronautics and Space Administration, Langley Research Center, whose support made this investigation possible. Special appreciation is extended to the personnel of the Propulsion Branch, Langley Research Center, for their advice and assistance throughout the course of the investigation.

VIII. APPENDIX

The following components constitute the interferometer:

Component	Manufacturer	Quantity
Klystron, 40V10	OKI Electronics	1
Power Supply, 940	TRG	1
Oil Bath, 946 A	TRG	1
Isolator, A110	TRG	1
Attenuator, A510	TRG	2
Coupler, A559	TRG	2
Frequency Meter, R532A	Hewlett-Packard	1
Thermistor Mount, R486A	Hewlett-Packard	1
Circulator, A164	TRG	1
Attenuator, A522	TRG	1
Hybrid Ring, A600	TRG	4
Termination, A580	TRG	2
Phase Shifter, A526	TRG	1
E-H Tuners, A620	TRG	4
Crystal Mounts, A970	TRG	4
Crystals, IN53	Sylvania	4
Phase Shifter, A528	TRG	1
Mode Transition, A693	TRG	1

The following additional instruments were used in conjunction with the interferometer:

Standing wave meter, 415E	Hewlett-Packard	1
Power Meter, 431C	Hewlett-Packard	1
Oscilloscope, 564	Tektronix	1
Tape Recorder, 2000	Hewlett-Packard	1
Differential Amplifier, 2470A	Hewlett-Packard	2