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DEVELOPMENT AND USE OF ULTRASOUND AND MICROWAVES TO EXPLORE THE SEALED BOAT-PIT SOUTH OF THE GREAT PYRAMID

PRESENTED BY

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SUMMARY

A research program was carried jointly between California State University , Sacramento and Cairo University, to develop microwave and ultrasonic techniques to image archeological sites. The microwave equipment was used to make an image of the boat pit south of the Great Pyramid.

In order to reach the objectives the equipment was designed in California then reassembled, tested, and caliberated at Cairo University.

During a second phase, tests were conducted at the boat museum and on the rocks outside the museum to determine if microwave could penetrate the required 1.7 meters of rock (slabs). Two microwave bands were used : 0.5 to 1 GHZ (30 cm resolution), and 2.6 to 3.95 GHZ (11 cm resolution). With the present equipment, the lower band could penetrate the rock.

After that data was collected to make an image. This was done both inside the museum for a reference with an empty pit, and over the unopened boat pit. Because of limited time and an anceint wall covering most of the unopened boat pit cover, only enough data was collected to make a cross sectional image across the third rock from the key. The data indicates that there are reflecting objects in addition to the bottom of the rock cover, and the base of the pit.

I. Introduction

The purpose of this research work is to develop ultrasound and microwave equipment and to use this equipment to detect archaeological chambers in Egypt. The ultrasound is primarily intended for use in rock, the microwaves for

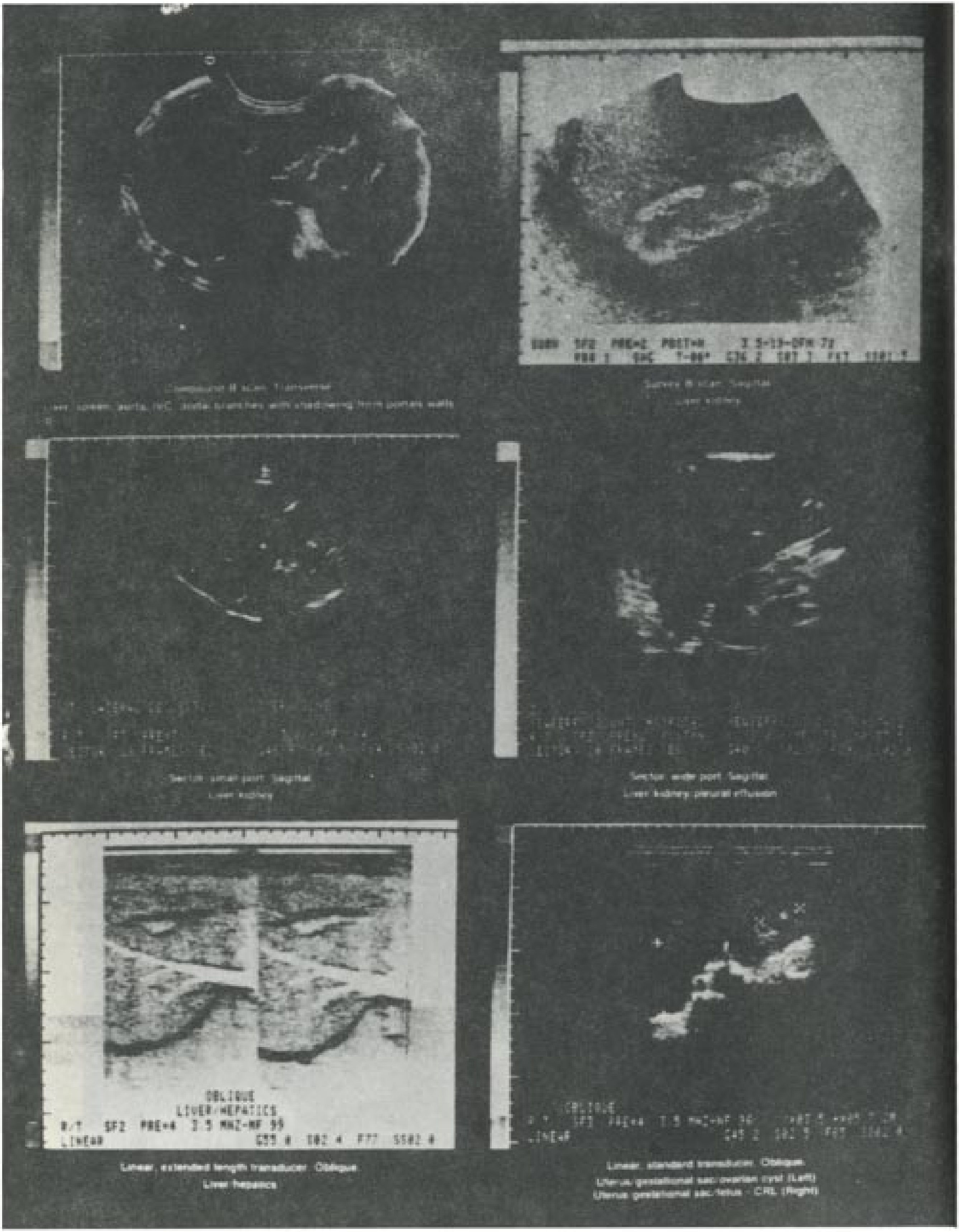
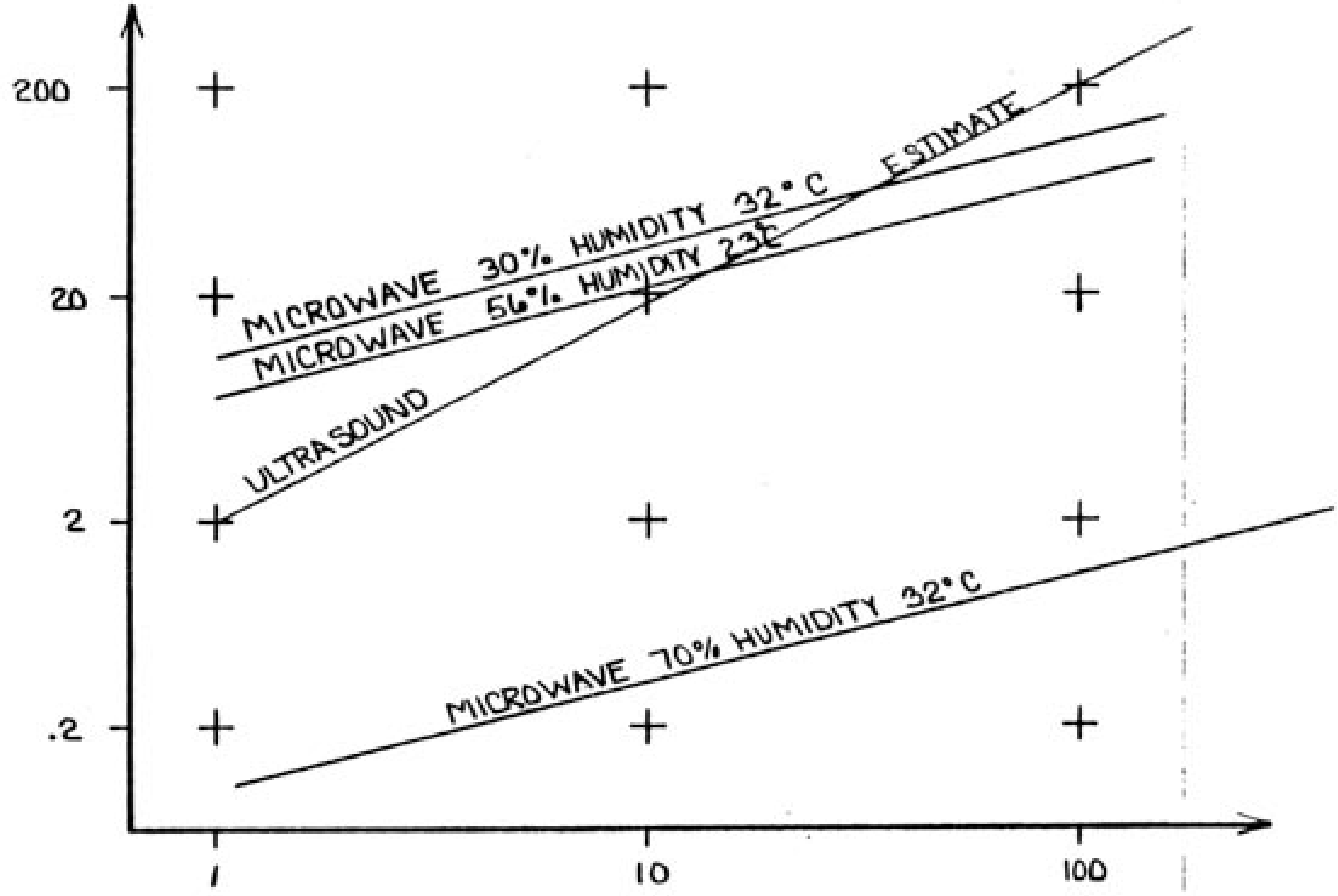


Fig.1 Ultrasound Image of Abdominal Organs



LOG WAVELENGTH (CM)

ASWAN LIMESTONE PENETRATION RANGE

FIGURE 2

both rock and sand. This equipment differs from that previously used in that the resolution is higher, and the final result is an image displayed on a television monitor. The initial application of the microwaves was to detect and image the contents of the boat pit south of the Great Pyramid at Giza. In the long term it is the intent to transfer the equipment and technology to Cairo University for systematic searches throughout Egypt.

II. Background

There were two developments in the past decade that provided the technical basis for this effort. The first was the pioneering effort of SRI in adapting modern sensing techniques to archaeology. The second was the rapid development of ultrasonic imaging technology for medical diagnosis.

Soon after Professor Alvarez of Lawrence Radiation Labs sucessfully used cosmic rays to X-ray the Chephren pyramid in Giza, SRI began a remarkable series of programs using other probes to assist in detecting archaeological artifacts. These included microwaves, infrared, electrical resistivity, magnetic field and ultrasound. In particular, they found that ultrasound worked quite well in solid rock. This was effectively demonstrated by bouncing an ultrasound pulse off the tomb of Ramsis VI from Tutankhamon's tomb. One of our proposed projects is within a hundred meters of this equipment.

SRI also tried to use microwaves (radar) to pentetrate the pyramids at Giza. This was not successful because of the unexpectedly high moisture level in these pyramids. Microwaves will penetrate only very dry materials. For example, the sand covering the tombs at Saqqara is practically transparent. Moderate penetration should also be expected in the limestone in the Valley of the Kings, or any rock or sand exposed to low relative humidity.

Medical electronics -- medical ultrasonic imaging in particular -- also underwent rapid development. Echo encephalography was used to diagnose head injuries by bouncing an ultrasound pulse off the midline of the brain in much the same manner as SRI did in the Valley of the Kings. There-after, a "B-Scan" imaging system, wherein an ultrasound probe connected to articulated arms was scanned across the body, became popular. This technology resulted in a cross-sectional image of the body displayed on a television monitor (see Figure 1 A and B). Mechanical scannner (Figure 1 C and D) and linear transducer arrays (Figure 1 E and F) soon followed. Phased array imaging, which uses no moving parts to produce an image, was introduced most recently.

The microwave project at the boat pit was based on B-scan technology but future projects will use image reconstruction based on phased array technology.

As SRI indicated in its final report, no attempt was made by them to optimize either the electronics or the transducer -- only to demonstrate feasibility. Echoes from unknown sources were found below Belzoni's Chamber in the Chephren Pyramid and in the vicinity of the tombs of Tutankhamon and Ramsis VI in the Valley of the Kings. However, no additional resources were available to determine if these were faults in the bedrock or other Chambers built by man. This could be resolved by imaging, as man-made chambers are typically much more regular in shape than natural faults.

III. Comparison of Microwaves and Ultrasound Imaging

Both microwave and ultrasound probes have been designed into the imaging system, although only microwaves have been used in Egypt. Each has relative advantages and disatvantages.

Ultrasound has the advantage of penetrating rock for great distances. Useful images in excess of 100 meters might be expected in the Valley of the King. Ultrasound cannot practically penetrate air . Thus, the walls of a chamber may be imaged, but not the contents of the chamber.

Microwaves have better penetration in dry sand than ultrasound, but generally less penetration in rocks. The penetration is controlled more by the moisture level of the material, than the material itself. For example, the high humidity levels in the giza pyramids limit penetration to about one meter, but tens of meters might be expected in the dry sands at Saqqara or the limestone in the Valley of the Kings. The rocks covering the boat chambers at Giza will be relatively tansparent during cool, dry weather, and more opaque after a rain or during hot, humid weather.

Microwaves easily penetrate air. Thus, microwaves can be used to image the interior of any detected chambers. Archaeologists prefer to know the contents of the chamber because rapid deterioration of the contents may occur after opening due to expodure to the atmosphere. If the contents are known before opening, the archaeologists can be prepared to provide immediate protection for any perishable materials.

What size objects might be seen in the images? Objects can be detected if they are a wavelength or larger. Longer wavelengths are needed for penetrating power. A graph of maximum penetration vs wavelength for both microwaves and ultasound for "Aswan Limestone" is shown in Figure 2. Objects of 10 cm in size can be seen in dry rock with microwaves and in any rock with ultrasound to about 20 meters. Microwaves are superior in sensitivity at shorter ranges, and ultrasound at greater ranges. At high humidity, microwaves are practically useless.

From this discussion, it is easy to see that ultrasound and microwaves complement each other. Ultrasound provides the great penetrating power in rocks, and microwaves provide penetrating power in dry sand as well as the ability to image the contents of chambers.

IV. Properties of Microwaves

For purposes of imaging, microwaves and ultrasound are remarkably similar. The microwave wavelengths that were used in this project are comparable to ultrasound wavelength proposed for future projects. Two microwave bands were used: 0.5 - to - 1 GHZ and 2.6 - to - 3.95 GHZ. The following table shows corresponding microwave and ultrasound center frequencies for the same wavelength in rock, assuming a microwave reflective index of 3 and ultrasound velocity of 10^5 cm/sec.

Microwave Center Frequency	Wavelength in Rock	Corresponding Ultrasound Center Frequency
0.75 GHZ	13.3 cm	7.5 KHZ
3.275 GHZ	3.0 cm	33.3 KHZ

Table 1 Microwave and ultrasound Comparison

The relationship between frequency f, wavelength λ, and velocity v, is

$$f\lambda = v \qquad \text{Equation 1}$$

For air $v_A = c = 3 \times 10^{10}$ cm /sec which is the velocity of light in air. In rock the velocity is c/n where n is the relactive index, typically 3 from measurements made by SRI.

For microwaves that are incident normal to the surface, the reflection coefficient for the amplitude (voltage) of the reflected wave is

$$R_c = \frac{n_2 - n_1}{n_2 + n_1} = \frac{v_1 - v_2}{v_1 + v_2} \qquad \text{Equation 2}$$

Where v and n are the propagation velocities and refractive indexes of the two media. Note that density does not enter into the formula as with ultrasound. As a consequence, microwaves can penetrate into air cavities to image, for example, the interior of the boat pit. In fact, the reflection coefficient between rock (refractive index = 3) and air is

$$R_c = \frac{3 - 1}{3 + 1} = \frac{2}{4} = 50\% \qquad \text{Equation 3}$$

compared with 99% for ultrasound.

The relation between beam shape and aperture is the same for ultrasound and microwaves. As a consequence, microwave and ultrasound beams of the same wavelength and aperture have essentially the same lateral resolution.

V. Swept Fequency Fundamentals

In the microwave front end, the method of achieving range resolution is depicted in Figure 3. The microwave source creates a signal

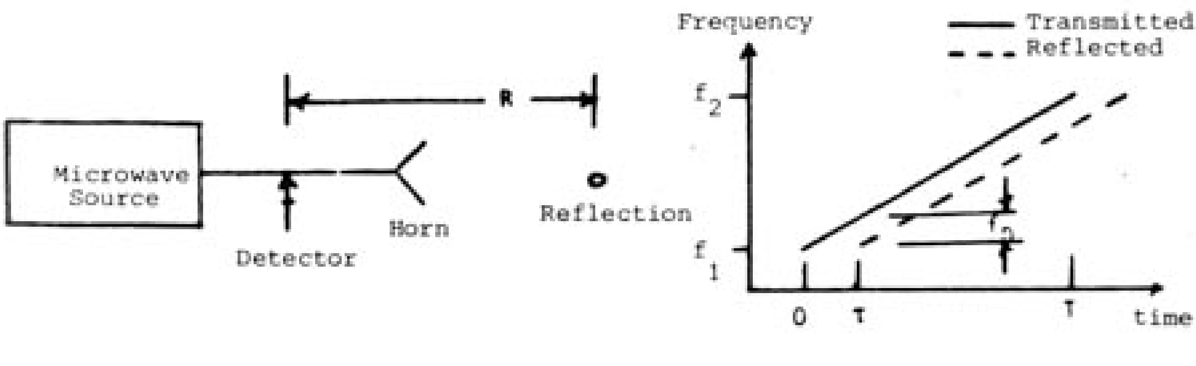


Fig. 3 Swept Frequency Principle

that sweeps a wide band of microwave frequencies from f_1 to f_2. The detector sees this signal as well as the one reflected from a target. If the target is a distance R away, the second signal will be delayed

$$\tau_0 = \frac{2R}{v} \qquad \text{Equation 4}$$

where v is the velocity. Because the detector diode is nonlinear, it will create the sum and difference frequencies. The difference frquency is the critical one, for it will be constant if the sweep is linear, and proportional to R. From similar triangles:

$$\frac{f_D}{\tau_0} = \frac{f_2 - f_1}{T} = f \qquad \text{Equation 5}$$

where f is the slope of the detected frequency

$$f_D = f' t_0 = \frac{2f R}{v} \qquad \text{Equation 6}$$

This frequency can be determined by taking the finite fourier transform of the detected signal S(t).

$$F(w) = \frac{2}{T}\int_0^T S(t)e^{-iwt}\,dt \qquad \text{Equation 7}$$

To be used in imaging algorithms the "echo" must be expressed as a function of propagation time. This time is related to the transform variable w as τ_0 is to f_D, i.e.

$$w = 2\pi f = 2\pi f' \tau \qquad \text{Equation 8}$$

so the transform can be rewritten

$$F(\tau) = \frac{2}{T}\int_0^T S(t)e^{-i2\pi f'\tau t}\,dt \qquad \text{Equation 9}$$

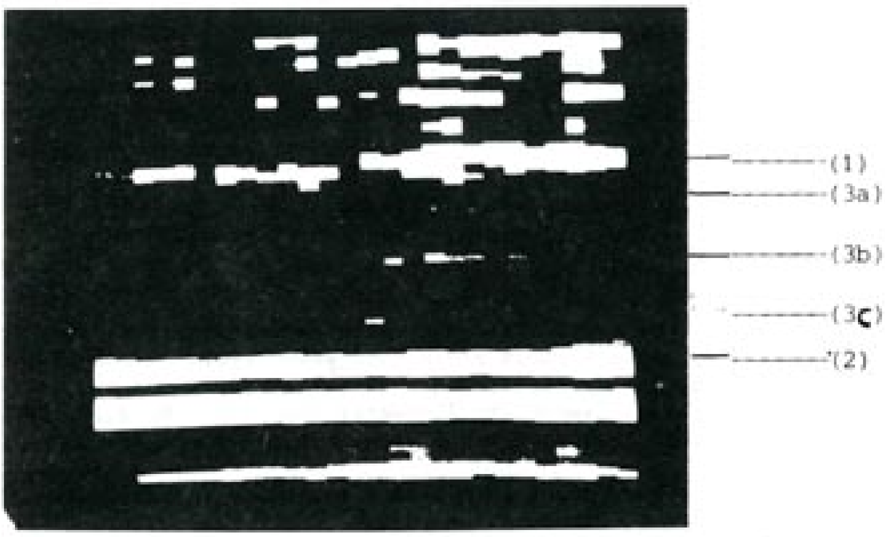


Figure 4 Cross sectional image across the third rock from the Key of the unopened pit.

This figure shows the following indications:

1. Reflection from the bottom of the covering slab of the rock (due to change of medium from rock to air).

2. A very strong reflection from the bottom of the pit.

3. Reflection from the objects inside the pit which would indicate a flat object (3b) at about half the hight of the pit (there might be some layers underneath that would give weaker reflections), some small longitudinal objects at different hights (3a, 3c).

The results obtained indicate the presence of some ojects, underneath the third slab of the pit, but it also shows that some more effort should be done to increase sensitivity of the equipment to detect weaker reflections, and to obtain better resolution to detect small objects and get more details.

A convenient procedure is to take the power spectrum. This will produce a (sin x/x) - type distribution for each target. This spectrum is always positive. The B-scan image of figure 4 is made by ploting the power spectrum along the vertical axis and distance across the boat pit along the horizontal axis.

VI. Electronic Circuits

The solid state microwave oscillators that are used have two input signals and a microwave output. One that we have been using requires +15 volts for power and a 0 to 19 volt signal to sweep the frequency from 2.507 to 3.790 GHZ. The output frequency-vs-voltage is shown in Figure 5.

A convenient interface circuit for operating the radar is shown in Figure 6.

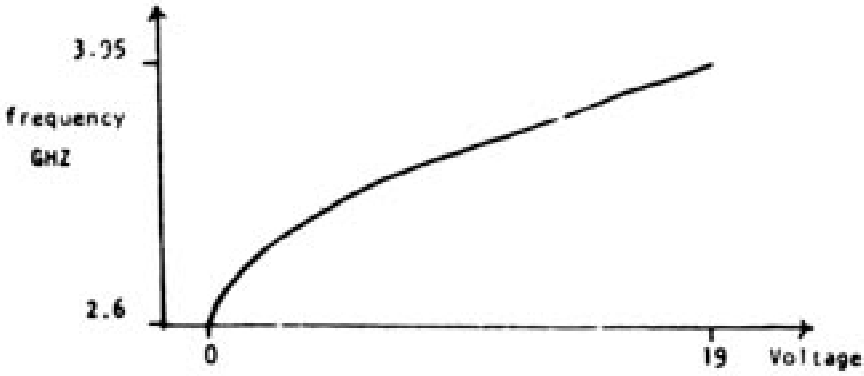


Fig.5 Fequency Calibration Curve

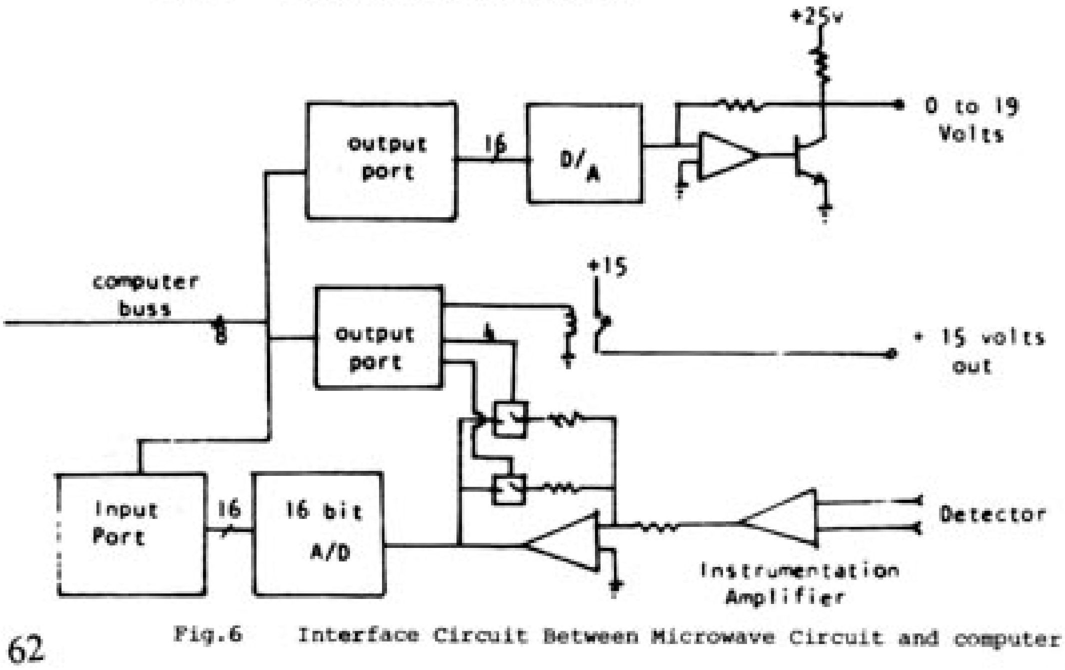


Fig.6 Interface Circuit Between Microwave Circuit and computer

A frequency is selected by calculating, from internal look-up tables, the appropriate voltage for the D/A converter. The detector voltage is then digitized and read into the computer. The power to the microwave circuit can then be shut off to obtain a zero reading to correct any drift in the instrumentation amplifier.

The instrumentation amplifier was chosen because there is often much 50 HZ or 60 HZ signals on the waveguide due to pickup from commercial power sources. The instrumentation amplifier typically has more than 100 db of common mode rejection. This output goes through an amplifier with gain selected by the computer. If, after digitizing an entire set of data, there are no codes in the upper range of the A/D converter, the gain can be increased under software control to utilize the entire dynamic range of the A/D converter. The gains can be set in 1, 3, 10, 30, etc. steps.

VII. Summary

Utilizing the circuit just shown, the procedure for obtaining a B-scan image is as follows:

1. Digitize the detected signal at equal increments of frequency. The voltage required to do this is obtained from the calibration curved supplied with the microwave source.

2. Correct the data by subtracting a signal corresponding to that detected and corrected with no target in the beam.

3. Take the transform with equation 9.

4. For each position across the pit, plot the transform vertically and position horizontally.

VIII. Work Done During the First Visit

Microwave and computer equipment arrived at Cairo University with the American team from California State University, Sacramento, on September 27, 1985 to make "images" of the unopened boat pit south of the Great Pyramid at Giza.

The equipment was assembled, tested, and caliberated at Cairo University.

Tests were conducted at the boat museum and on the rocks outside the museum to determine if microwave can penetrate the required 1.7 meters of the rock (slabs). Two microwave bands were available : 0.5 to 1 GHZ (30 cm resolution), and 2.6 to 3.95 GHZ (11 cm resolution). With the present equipment, the microwave lower band could penetrate the rock.

Data was collected to make an image. This was done both inside the museum for a reference with an empty pit, and over the unopened boat chamber. Because of limited time and an ancient wall covering most of the unopened boat pit cover, only enough data was collected to make a cross section image across the third rock from the key. A cusory review of the data indicates that there are reflecting objects between the bottom of the rock cover, and the base of the pit.

Later on, computer processing was used to produce an image out of the data collected during the field visit. The image obtained is given in figure 4.

IX. Tentative Conclusions of the Results

The conclusions that were obtained at the time of the experiements were written and recorded in a report delievered to the Antequities Organization as follows:

1. The unopened boat pit is not empty.

2. Microwaves can be used to penetrate up to 2 meters of limestone and image objects in the air chamber beyond the 2 meters.

3. The difference in signal strength obtained when testing the opened pit (inside the museum) and the closed pit (higher signal strength), indicated, most probably, that the average humidity inside the second pit is much lower than the first one (which is already maintained at 50% level). $

- Based on the image obtained, a redesign of the equipment was suggested in order to reach two objectives.

  . Obtaining a stronger signal.

  . Obtaining better resolution.

The new design will incorporate different kind of antennas and a microwave generator that would allow a range of frequency from 0 to 4 MHz. This would result in a resolution of about 4 cm, which means objects of size greater than 4 cm would show up in the images obtained. The signal processing will be revised from B-scan processing to images reconstructed from synthetic aperture algorithms.

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§- Compare prediction with the actual value of 84 ± 2 %, quoted by Tans et al. elsewhere in this Proceedings. The Editor.

References :

"Applications of Modern Sensing Techniques to Egyptology", and "Electro-magnetic Sounder Experiments at the Pyramids of Giza", prepared jointly by the Organization of Antiquities, Ain Shams University, and SRI; published by SRI International, Menlo Park, California, 94025 in 1977. Project Leaders from SRI: Lambert Dolphin and Roger Vickers.

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