INFRARED LASER / SONAR BEAM INTERACTION AT SEA-AIR INTERFACE

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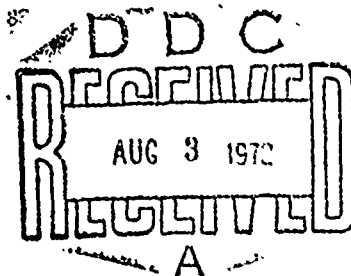
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Abstract

A novel technique for direct communication between an aircraft and a
submarine, based on the use of laser beams in air and sonar beams
in the sea, interacting at the sea surface, is described. Initial
laboratory feasibility studies are described.

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The capability of establishing a direct secure communication link
between an aircraft and a submarine is of considerable interest in
naval technology. At present, an indirect link can be realized by
relaying radio messages via a high power VLF installation; on the
other hand, direct links cannot be readily implemented because of
large losses associated with the propagation of electromagnetic and
acoustic waves respectively in the sea or in air.

As an example, if a collimated laser beam, operating in the blue-green
region, is considered, it is found that an attenuation of the order of
1 dB/m and a spreading of the beam occur in the sea and a reflection
loss of 6 dB and a refraction deviation of the beam direction at the
sea surface.[1]

Another approach which has been studied is based on the use of high
power infrared laser beams to generate acoustic waves in the water by
Q switching [2,3,4]; for example, experiments conducted by Naval Ordnance
Laboratory scientists have demonstrated that, using a CO_2 laser, it is
indeed possible to generate such waves, but the efficiency of power
transfer is very low, of the order of 10^{-4}, because the pressure of the
generated acoustic waves is limited by the presence of the atmospheric
pressure, and because the waves have spherical shape, with amplitude
decaying with distance R as $1/R^2$.

In the following we discuss a communication link technique in which the propagation losses are reduced by utilizing a laser beam in air and a sonar beam in the sea; by recourse to efficient interaction phenomena at the sea surface, transfer of information from one beam to the other one is accomplished. The technique has been investigated experimentally with laboratory models.

At the outset we assume that the sea surface is a plane, neglecting surface waves. The technique for communications from submarine to aircraft is illustrated in fig.1: a collimated laser beam, modulated by frequency shift keying, is directed to the sea surface, where it establishes a wave distribution at the sonar acoustic frequency. A collimated laser beam from the aircraft is bounced off ω the sea surface and returned to the aircraft receiver; because of the surface wave distribution the reflection direction of the laser beam varies with time, acquiring a spatial angular modulation of the same type as that carried by the sonar beam. The technique for communication from aircraft to submarine is illustrated in fig. 2. A high power infrared laser beam of CO_2 type, with on-off amplitude modulation, is directed at the sea surface where its energy is absorbed and converted into heat; thus the temperature of the illuminated surface layer varies with time, following the modulation of the laser. A collimated sonar beam, bounced off the sea surface and returned to the submarine, is on-off phase modulated on traversing the heated surface layer.

In both cases a laser beam is used in air and a sonar beam in the sea; in addition, one beam "writes" the message on the sea surface and the other one "reads" it out.

An analysis of the above techniques may be developed as follows. It is assumed that the sonar beam is characterized by a plane sinusoidal wave, propagating along the x axis; indicating with ψ the scalar velocity potential function, one has

$$\psi = \psi_m \cos (kx - wt)$$

where $k = 2\pi/\lambda$. The particle velocity $\bar{u}$, the pressure p and the displacement ξ are obtained from the fundamental relationships

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$$\bar{u} = -\bar{\nabla}\psi \ , \quad p = \rho \frac{\partial \psi}{\partial t} \quad , \quad \xi = \int u \, dt$$

where ρ is the water density. There follows

$$p = \omega\rho \, \psi_m \sin(kx - wt)$$

$$\xi = \frac{k \, \psi_m}{\omega} \cos (kx - wt)$$

Indicating with $\mathcal{O}_s$ the acoustic power density one has

$$\mathcal{O}_s = P_m^2 \, / \, 2\rho v$$

where v is the wave propagation velocity and P_m is the amplitude
of the pressure; it follows that the amplitude of the displacement
is $\frac{1}{\omega} \sqrt{2 \mathcal{O}_s / \rho v}$. Although this quantity is very small
(for ex. at 25 kHz and 1w/cm^2 it is of the order of 10^{-4} cm) the
displacement is sufficient to cause a corresponding oscillatory
angular displacement of the direction of the reflected laser beam.
Detection of such modulation is obtained with a photodetector after
converting it to amplitude modulation, by recourse to a suitable grating
or aperture array inserted in the beam path.

Laboratory tests have been conducted using a cylindrical water
tank of 3 ft diameter, in which an immersed transducer generated acoustic
waves in the range from 25 kHz to 225 kHz and with power density variable
between 10^{-7} and 10^{-4} w/cm^2. Readout was obtained with a HeNe laser
beam (fig 3) using a wire mesh for the modulation converter and a
photomultiplier for the detector. A Stoddart type superheterodyne re-
ceiver was utilized to amplify the detected signals and to measure
the signal to noise ratio. As shown in fig 4, the signal to noise ratio
was practically independent of the frequency of the acoustic waves
and varied from a minimum of 4 at 10^{-7} w/cm^2 to a maximum of 40
at 10^{-4} w/cm^2. It is believed that these values could be further .
improved by recourse to a more sophisticated modulation converter.
With reference to the system of fig. 2, we assume that a pulsed infrared
laser beam, delivering J joules per pulse at 10.6 microns, illuminates
a surface of diameter D at the sea surface; if the laser radiation

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is absorbed in a layer of thickness d, the corresponding increase of
the temperature is

$$\Delta\theta = \frac{4J}{4.185\,c\,\varsigma\,\pi\,D^2 d}$$

where c is the specific heat (c $=$ 1 cal/gm°C). Similarly, cooling occurs
at the termination of the laser pulse, and, thus, the temperature of the
illuminated surface layer varies at the rate of the laser beam pulses.

An acoustic wave, reflected at the said surface, experiences a cor-
responding variation of phase on traversing the layer, since the wave
velocity is a function of temperature

$$v = 1.46 \times 10^5 + 620\,\theta \qquad cm/sec$$

where θ is the temperature in °C. Indicating with w the angular fre-
quency of the acoustic wave and with $\emptyset = 2wd/v$ the phase delay on
traversing the surface layer back and forth, the incremental phase va-
riation corresponding to the temperature variation $\Delta\theta$ is

$$\Delta\psi = -\frac{2wd}{v^2}\frac{dv}{d\theta}\Delta\theta = -4.13 \times 10^{-9}\frac{wJ}{D^2} \qquad rad$$

where J is in joules, D in cm. It is noted that $\Delta\emptyset$ is independent
of the thickness d and is proportional to wJ/D^2. As an example,
letting w $=$ $2\pi 10^5$ rad/sec, J $=$100 joules, D $= 10^3$ cm one finds $\Delta\emptyset =$
$- 26 \times 10^{-8}$ rad.

Laboratory tests were conducted using a 1.5 ft diameter tank in which
two transducers, respectively for transmission and for reception of the
acoustic beam, were immersed. A 60 kHz acoustic frequency was selected;
for simplicity a tungsten infrared lamp, rated at 250 watts, with me-
chanically chopped beam, was used as illuminator, yielding a power density
estimated of the order of 10^{-2} w/cm^2. In practice a CO_2 laser would
be employed, in order to obtain higher power density and higher absorption
at the sea surface (fig 5).

The incremental phase variation of the water surface temperature was
measured with a thermocouple, whose junction was placed at the water
surface; it was necessary to dissipate the heat delivered to the confined
tank, by recourse to continuously running tap water, flowing in an
immersed copper tube coil. In the sea environment the heat dissipation

occurs automatically because of the large mass of water and of the action
of wind waves. The cooling rate determines the amplitude of the incremen-
tal temperature variation of the surface layer; in our experimental con-
ditions it was found that heating raised the surface temperature from 21.0
$^{\circ}$C to 21.27°C in 5 minutes at a rate of about 10^{-3} C/sec; cooling
occurred at a somewhat lower rate of the order of 0.4×10^{-3} $^{\circ}$C/sec. The
corresponding phase variations, measured aith a phase comparator having sen-
sitivity 1.5×10^{-2} V/phase degree , were 0.4 phase degrees/sec $= 6.6 \times 10^{-3}$
phase rad/sec for heating and 0.11 phase degrees/sec $= 1.9 \times 10^{-3}$ phase rad/sec
for cooling; the amplitude of the signals obtained at the comparator output
were respectively 6 mV/sec and 1.6 mV/sec(fig 6).

These results demonstrate the feasibility of utilization of the absorption
of infrared radiation at the sea surface as interaction phenomenon between
infrared radiation and sonar waves.

The previous results have been obtained in ideal laboratory conditions,
in which the water surface was assumed to be a plane. In practice it is
necessary to extend the investigation to the case in which water waves
are present. The greatest difficulty is found with reference to the readout
beam, since the water waves cause a variation of the angle of incidence
and of the direction of the reflected beam. The problem may be solved by
automatic control of the direction of the incident beam, such as to optimize
the reflected beam power at the receiver. The control signals are obtained
by sampling the reflected beam along two perpendicular direction S, measuring
the rate of change of the collected power, and using them to adjust the
direction of the incident beam so as to optimize the overall power. ·-

Another difficulty is presented by the various sources of noise at the
sea surface and within the sea medium; at the surface capillary waves in-
terfere with the acoustic waves, and within the medium thermal fluctuations
introduce incremental fluctuations of the phase of the readout beam.
However, since the signal frequency is known and the bandwidth is limited,
these noise problems may be solved by standard filtering and cross-corre-
lation techniques.

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Conclusion

A novel communication technique between aircraft and submarine which utilizes a laser beam in air and a sonar beam in the sea, using their interaction at the sea surface for modulation transfer, has been described. Basic verifications, conducted with laboratory models, have given promising results, in agreement with the analysis. A discussion of the application of the technique in real environment has been presented.

Acknowledgment

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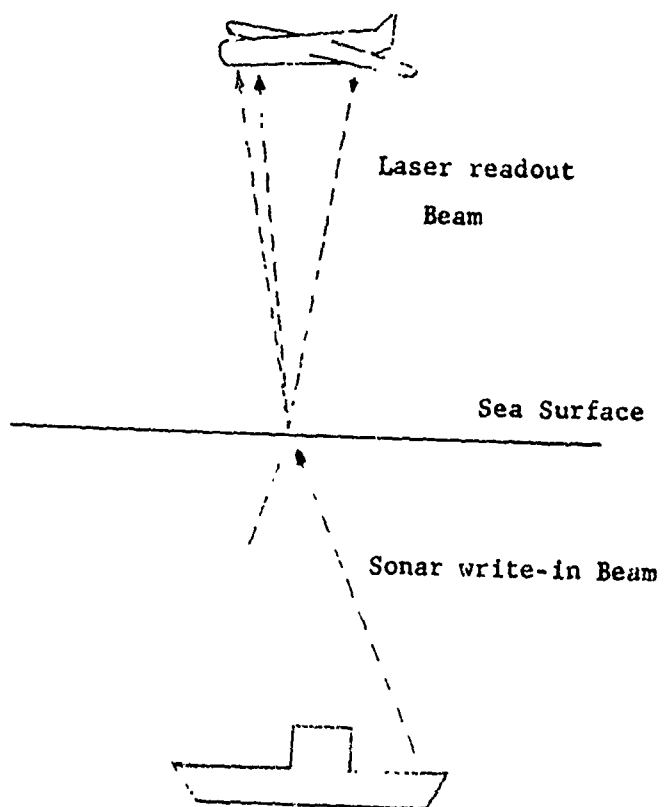and water - N O L - NOL TR 69-166-1970

Fig 1- Communication link from submarine to aircraft

Laser write-in Beam

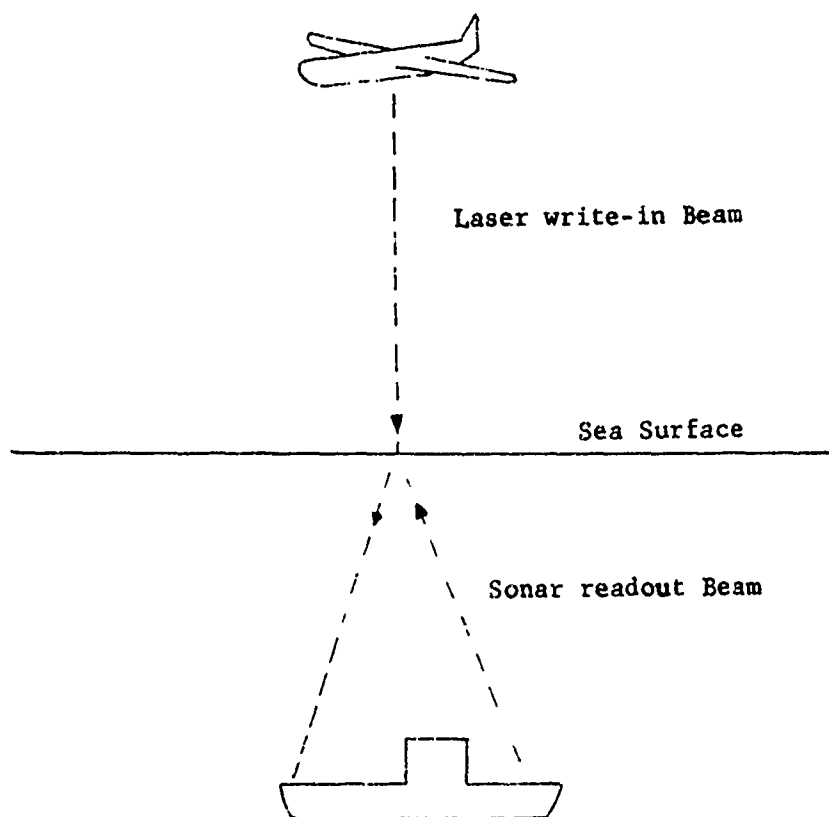Sea Surface

Sonar readout Beam

Fig 2 - Communication link from aircraft to submarine
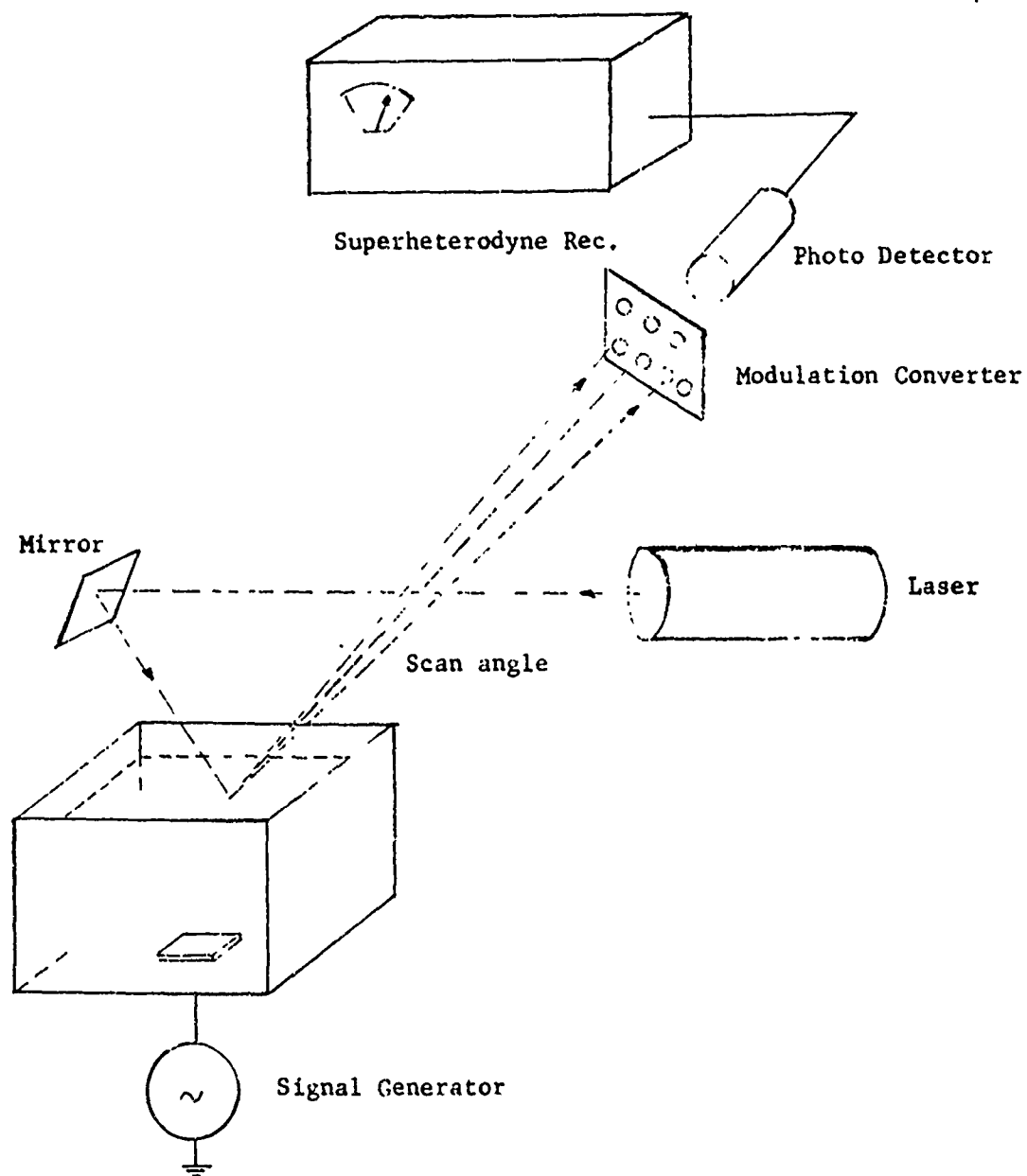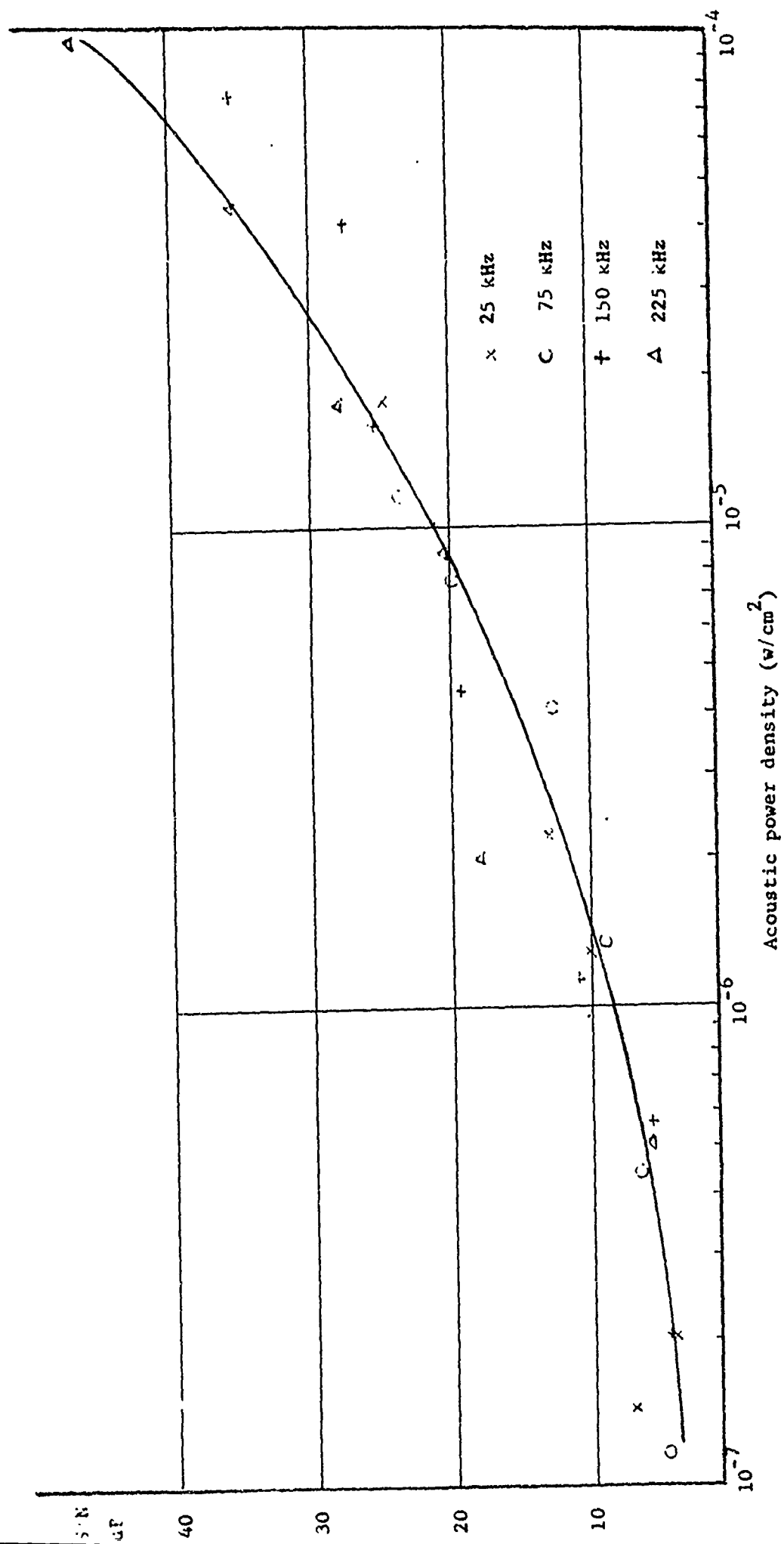
Fig 3-   Model for Water-to-Air Communication technique

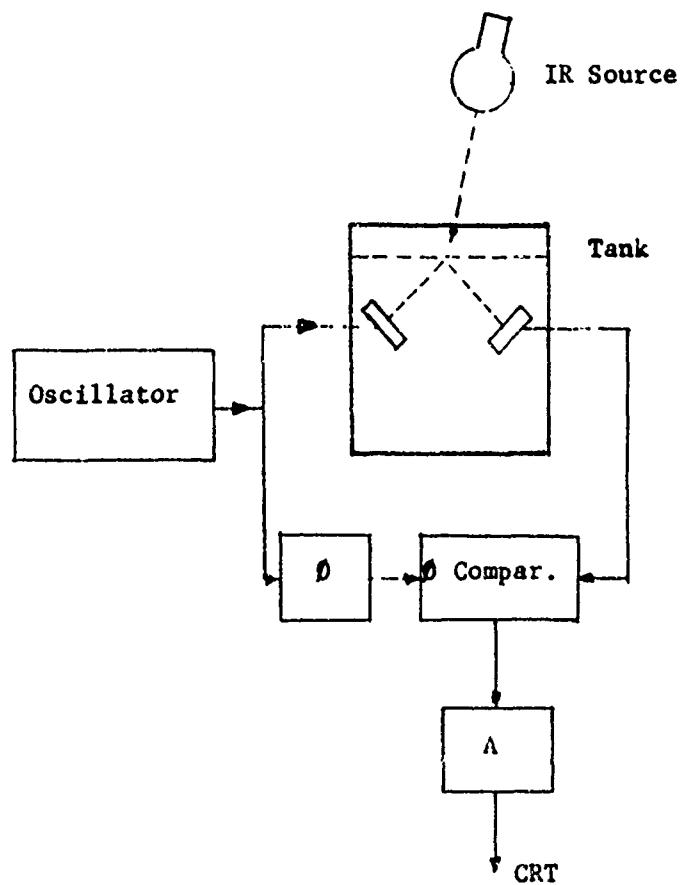**Fig 4- Signal-to-noise ratio versus acoustic power density**

Legend:
- × 25 kHz
- ○ 75 kHz
- + 150 kHz
- △ 225 kHz

Y-axis: S/N dB (40, 30, 20, 10)

X-axis: Acoustic power density (w/cm^2) (10^{-7}, 10^{-6}, 10^{-5}, 10^{-4})

IR Source

Tank

Oscillator

𝜙

𝜙 Compar.

Λ

CRT

Fig 5-   Model for experimental investigations of Air-to-Water
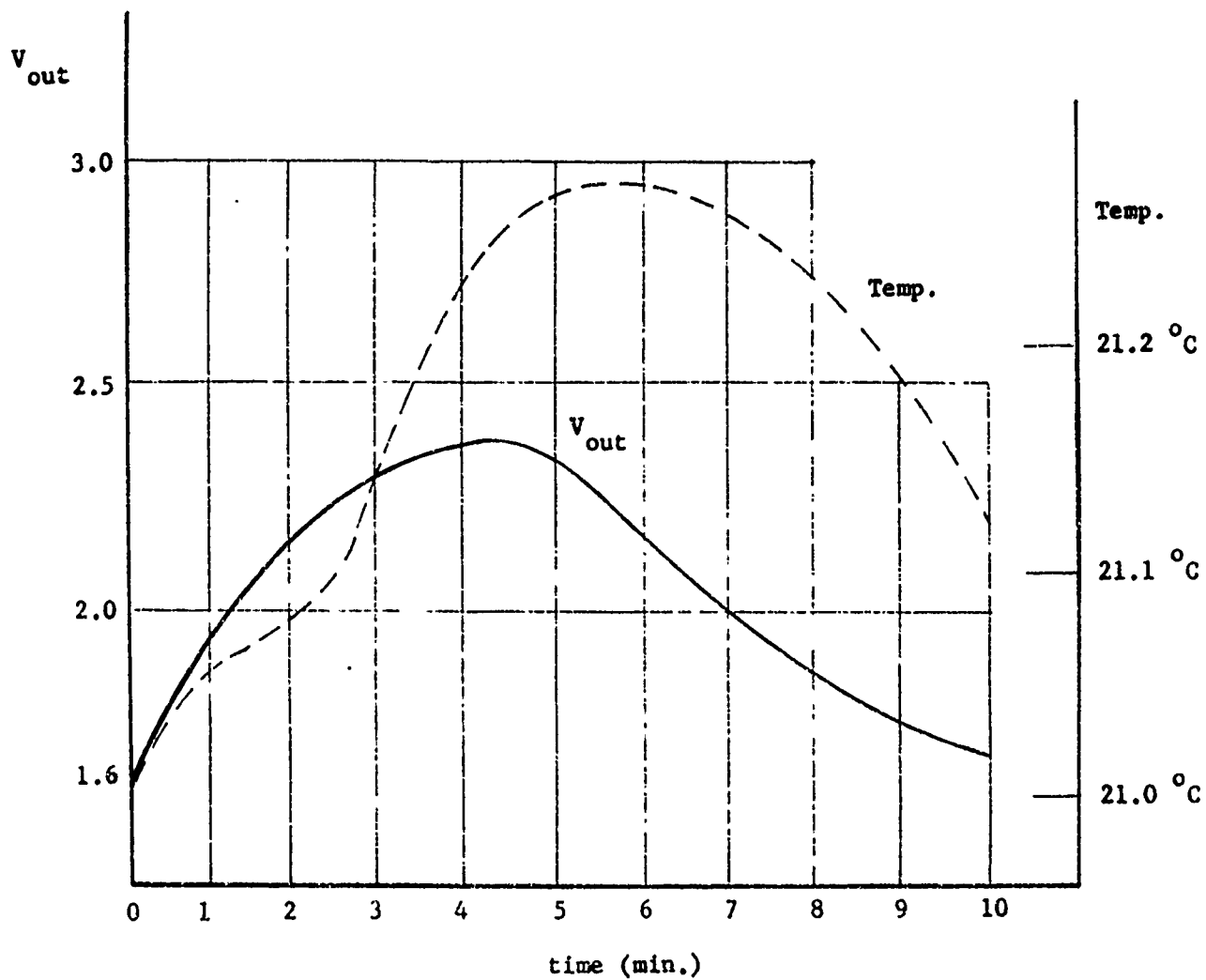
Communication · ₋nnique

Fig 6- Variation of surface temperature and modulation of phase of the acoustic wave by interaction with IR radiation.