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PARAMETRIC ARRAYS IN AIR WITH APPLICATIONS TO ATMOSPHERIC SOUNING

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Abstract.—The theoretical and experimental results are presented to demonstrate the character and utility of narrow beam parametric arrays operating in air. Beginning with the delineation of the field at low intensities (variation of pressure level and azimuthal response with increasing range) we expand previous work to include the self-demodulation of transients and high-intensity effects associated with acoustic saturation of the primary radiations. Effects peculiar to experiments in the atmosphere are also presented, such as the diurnal variation of temperature, humidity, and consequently absorption. Practical applications associated with the use of parametric arrays in atmospheric sounding are examined from the feasibility standpoint. It is concluded that normal diurnal variations pose no great difficulties, while the low parametric efficiency poses a nontrivial problem for applications requiring high source levels. Solutions to this problem are suggested.

1. Introduction.—Since its discovery in 1960 (1), the parametric array has been researched and developed predominantly in underwater acoustics. Only a few papers dealing with experiments in air have appeared in the archival literature (2-5). The notion of parametric arrays to air acoustics problems has been received with skepticism (6).

The purpose of the present paper is to expand the present knowledge of parametric experiments in air with a view toward assessing the potential of possible practical applications.

The parametric array generates a narrow, low-frequency sound beam with no side lobes through the nonlinear interaction of intense high-frequency radiations emitted from a small primary sound source. Three general types of parametric arrays have been identified and discussed in some detail (7). Each has its own characteristics and special theoretical models. Their distinction is based on the relative size and shape of the interaction region.

2. Experimental illustration of a parametric acoustic field.—As in any acoustic experiment, the transducer is usually of primary importance. Nonlinear acoustics requires intense radiation, which normally leads to a peak pulse power demand at the expense of a low duty cycle. Applications in air are further influenced by practical emphasis on 1) reasonable efficiency, 2) wide bandwidth, 3) good impedance coupling, and 4) low internal distortion.

The transducer used has a 5.7 cm diameter face consisting of 7 clamped plate resonators whose center frequency is displaced from that of the mass-loaded ceramic driver. The primary radiations are launched at the two resonances. Figure 1 illustrates the 0.56 m f/2 parabolic reflector mounted on a two axis rotator column, as well as a microphone and its supporting 6 m tower. (The face of the transducer is turned away from the reflector in this figure). The tower rides on a car rolling on a 250 m railway. A double FM radio link relays received signals for analysis as a function of range r from the source.

This equipment was used in a purely exploratory approach to air acoustics applications, with no particular detection or sensing requirements imposed. The resulting data of Figs. 2 and 3 demonstrate the acoustic field of primary and secondary radiations acquired in the course of some measurements in a dead calm atmosphere at 25°C and 77% relative humidity. The primaries were transmitted with an acoustic power on the order of 1 Watt. It
can be seen that the transducer beam is somewhat larger than predicted, giving the reflector an effective diameter of 0.34 m.

The far-field parametric pressure is modeled by the Westervelt formula (1). Good agreement between theory and experiment is shown in Fig. 3 for the sound pressure level of the 1 kHz difference frequency radiation. It can be seen that the experimental spot size is somewhat smaller than the predicted value. It is also about 6 times smaller than that which could be radiated linearly from the same effective aperture at the same 1 kHz frequency.

3. Atmospheric sounding. Remarkable advances in the use of acoustics to probe the atmosphere have been made since 1968 (6). Amongst the practical applications realized to date are profiling of the planetary boundary layer to study air mass inversions, the subsistence of inversion layers, mixing, thermal plumes, and gravity (internal) waves. These studies are quite significant in the air pollution and meteorologic disciplines. Also important are practical applications to Doppler sensing of wind speed, vertical profiling of wind velocity, the measurement of wind shear and the development of sensors for shear induced turbulence. These devices have been developed and tested for use at airports, as have combination acoustic and electromagnetic sensors which are also amenable to aircraft applications for the detection of clear air turbulence.

The attractiveness of acoustic sensors lies in the fact that the acoustic cross section for turbulence is some $10^6$ times greater than that for electromagnetic waves (6). It is predominantly the temperature differentials in the turbulent atmosphere that influence the acoustic cross section.

Atmospheric sounders can be deployed in several configurations (6). Simple monostatic sounders are usually mounted on a vertical axis and are operated like a depth sounding sonar to probe the atmosphere on the basis of echo amplitude. This configuration is modeled by the echosonde equation (8).
4. Applicability of parametric sources. As in any analysis there are advantages and disadvantages with each alternate approach. The quite attractive parametric radiation patterns, generated from small apertures, warrant a consideration of the nonlinear approach to atmospheric sounding. This is appropriate and timely as side lobe reflections from terrestrial features have recently been identified as sources of false structures in sounder records (10). Other potential advantages of parametric sounders exist.

The diurnal variations in ambient temperature and humidity affect the absorption and consequently the properties of the parametric array. Some typical values are plotted in Fig. 4. Over the range

$$P_R = P_T e^{-2\alpha R} \left[ \sigma_o(R,f) \left( \frac{C_0^2}{2} \right) \left( \frac{A}{R^2} \right) G \right], \quad (1)$$

where the received power $P_R$, transmitted power $P_T$, range $R$, pulse length $\tau$, aperture area $A$ are straightforward parameters. The effective aperture factor $G$ arises from the transducer directivity.

The acoustic cross section $\sigma_o$ is frequently approximated (9) by

$$\sigma_o = 0.0039 k^{1/3} \frac{C_t^2}{T_0} \quad (2)$$

where $k$ is the wave number, $T_0$ the mean temperature, and $C_t^2$ is the temperature structure parameter, which frequently varies from $10^{-3}$ to $10^{-4}$.

Several models have been developed for Doppler sensing of wind fields, ranging from the simple monostatic case to those involving three-dimensional triangulation (6,8).

Fig. 3: The acoustic field of difference frequency radiation, a) propagation curve, b) half-power spot size of the beam.

Fig. 4: Diurnal variations in parametric array properties over a typical summer day in Texas.

of values shown, the night time decrease in temperature and increase in humidity increases the parametric array length, $l_A = 1/(2a_0)$, and decreases the half-power beamwidth, $\theta_3 dB = 4 (\sigma_o/k)1/2$, while the effective source level is simultaneously increased. Since the 24 hour variation in array
length only spans ± 13%, the beam width ± 7%, and
the source level ± 12%, the diurnal effects do not
appear significant, especially since they can be
accounted for. This may be more difficult in
periods of transition from calm to violent weather,
or for use of the same array one day in a rain
forest, the next on a desert.

Perhaps a more serious concern is the relative
inefficiency of parametric arrays and their con-
sequent low source level. This usually restricts para-
metric applications to problems where the low
efficiency is not an issue, such as ocean depth
sounding and propagation is shallow water. The
efficiency issue is not trivial for applications
to atmospheric sounding.

For purposes of discussion, we can consider
source level requirements for an existing wind shear
sounder deployed at Dulles International Airport in
Washington D.C. by the National Oceanic and Atmos-
pheric Administration, Wave Propagation Laboratory.
The main transmitter of this system radiates 120
Watts in a 9° half-power beam at 1250 Hz from a
parabolic horn, 2 m in diameter. The extrapolated
source level is approximately 157 dB re 20 μPa rms
at 1 m. Although it would be ludicrous to seriously
compare this system to the simple experiment illus-
trated in the present paper, since it radiates less
than a Watt (at the primary frequencies), the fre-
frequencies are nonetheless similar while the beam-
width and source diameter of the experiment are
about 2 to 3 times smaller, respectively.

The question of increased radiated power now
arises. There are limits to arbitrary increases as
the primaries eventually go into shock which means
harmonic generation, increased absorption, and
eventual acoustic saturation. A useful model for a
largely plane wave parametric array in shock has
been discussed in reference 11, and results con-
cerning the parametric source level for the present
experiment are shown in Fig. 5. It can be seen that
although the slope of the amplitude response curve
changes from quadratic to linear in the shock region,
the amplitude of the difference frequency radiation
continues to increase with increase in primary power.
This is accompanied by an increase in parametric
beamwidth, (11) and simply means that acoustic
saturation ultimately limits the attainable source
levels, array lengths, and beamwidths (12).

![Fig. 5: High amplitude response of the parametric array experiment.](image)

5. - **Self-demodulation of transients.** The transmis-
sion of an intense cw pulse is accompanied by the
interaction of its sideband components to produce
a directive parametric transient of low frequency
content. The original model (13) predicting this
effect was derived for the axial pressure response
in the time domain. It shows a dependence on the
second time derivative of the square of the prima-
ry pulse envelope function \( f(t - x/c_0) \), in the
form

\[
p_t(x,t) = \frac{p_o^2 \gamma (1 + \gamma)}{32 \pi \rho c_0^2 \alpha} \frac{1}{t^2} \left[ f(t - x/c_0) \right]^2 \tag{3}
\]

Experimental verification of this effect in liquids
has been published (14).

The question arises as to the existence and
potential utility of the self-demodulation tran-
sient in air. The axial time domain data of Fig. 6
was acquired during the course of the present measurements to illustrate the effect. A dual beam oscilloscope was used to depict both the primary and demodulated signals resulting from transmission of an 18 kHz pulse at a range of 9.3 m. The difference in arrival times for these two signals is due to the geometry of the frequency selective receiver.

It can be seen that a demodulated transient was here obtained, in reasonable consonance with theory, despite the low power level of the present experiment. Systems producing hundreds of watts of radiated pulse power should be expected to generate fairly strong self-demodulation transients in the medium. Their bandwidths can be made quite large, with frequency responses extending down to the infrasonic region. Their directivity at these frequencies could be remarkably high. It is suggested that existing sounders be examined for this effect.

Also of potential interest is the application of directive parametric transients to turbulence research. Use of the parametric transient would appear to lead instantaneous wideband sensing through impulse response techniques. Other possibilities exist.

6.- Conclusions. The nature of parametric arrays in the atmosphere has been examined with theory and experiment. Practical applications have been suggested and considered from the feasibility standpoint. It was shown that diurnal variations in temperature pose no great problems in parametric array generation. The low efficiency and source level of this process is nontrivial. Applications requiring high source levels should employ spherically diverging primaries to circumvent the limiting effects of acoustic saturation within the interaction volume. The generation of directive, low frequency transients through the self-demodulation of primary pulses was identified as a viable process for air acoustics with possible implications for applications in infrasonics and turbulence research. Existing atmospheric sounders should be examined as sources of parametric transients.

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