REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)
15-04-2010

2. REPORT TYPE
Final Report

3. DATES COVERED (From - To)
1-Aug-2007 - 31-Oct-2009

4. TITLE AND SUBTITLE
Generation of intense low-frequency collimated sound beams by nonlinear acoustics and detection by a millimeter-wave vibrometer

5a. CONTRACT NUMBER
W911NF-07-1-0478

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
121000

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
John A Scales, Martin Smith, Brian Zadler

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Colorado School of Mines
Colorado School of Mines
1500 Illinois Street
Golden, CO 80401 -

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
51887-EV.1

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
In this work, we designed, developed and tested nonlinear ultrasonic arrays for the purpose of generating an intense, collimated beam of sound to be directed at targets such as buried landmines. In order to make a completely noncontacting system, with insonification via the nonlinear array, we also developed a sensitive millimeter wave vibrometer to detect the resulting ground motion.

15. SUBJECT TERMS
landmine detection, nonlinear ultrasonics, millimeter wave vibrometry, non-contacting acoustics

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		John Scales
					19b. TELEPHONE NUMBER
					303-273-3850

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Generation of intense low-frequency collimated sound beams by nonlinear acoustics and detection by a millimeter-wave vibrometer

ABSTRACT

In this work, we designed, developed and tested nonlinear ultrasonic arrays for the purpose of generating an intense, collimated beam of sound to be directed at targets such as buried landmines. In order to make a completely noncontacting system, with insonification via the nonlinear array, we also developed a sensitive millimeter wave vibrometer to detect the resulting ground motion.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

A low-cost millimeter wave interferometer for remote vibration sensing, M. Smith, J. Scales, M. Weiss, B. Zadler, in press, Journal of Applied Physics

Number of Papers published in peer-reviewed journals: 1.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Annual Army Landmine Meeting, 2008 and 2009.

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

A low-cost millimeter wave interferometer for remote vibration sensing, by M. Smith, J. Scales, M.Weiss, B. Zadler, 2008 international meeting: Progress in Electromagnetics Symposium (PIERS).

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 1

(d) Manuscripts

Enhancing the nonlinear conversion in ultrasonic parametric arrays, to be submitted to Journal of Applied Physics.

Number of Manuscripts: 1.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Brian Zadler	0.75
FTE Equivalent:	**0.75**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
John Scales	0.00	No
Manoja Weiss	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
Daniel Gibson	0.00
Scott Schafer	0.00
FTE Equivalent:	**0.00**
Total Number:	**2**

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 2.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 2.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Producing an intense, collimated beam of low-frequency sound *via* nonlinear interaction in air (parametric array)

The goal of this task is to produce an intense, collimated beam of low-frequency (200-1000 Hz) sound that can be directed to insonify a chosen target area.

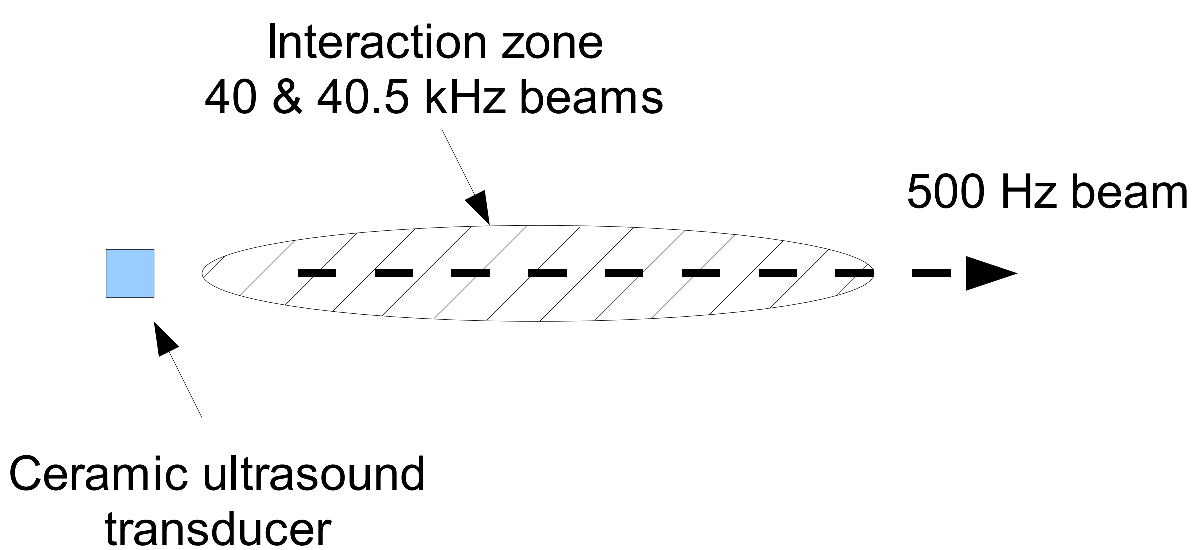
A straightforward approach to producing such a beam is to use a linear array of low-frequency sources in an *end-fire* configuration. The angular width, δ, of a monochromatic beam is (Barger, 1998)

$$\delta=\frac{\lambda}{L}$$

where λ is wavelength and L is the length of the array. For a 5° beam-width we would need an array about 11λ long. At 1000 Hz a 5° array would be 3.6 meters long; at 500 Hz, 7.2 meters long, and at 200 Hz 18 meters long.

A 7 meter linear array would be cumbersome, space-consuming, and difficult to manipulate. We avoid these problems by exploiting *parametric array technology* (Westerveldt, 1963) which allows us to replace a physical array by a virtual array created by nonlinear propagation of intense sound beams. It's helpful to step through a specific example of this process: the figure below diagrams the process approximately as it occurs in the specific parametric array we built for this project.

On the left is a single ceramic ultrasound transducer. In our case this is a cylindrical element a few inches on a side which produces an ultrasonic beam at 40 kHz this is about 14° wide. We drive the transducer with the sum of a 40 kHz and a 40.5 kHz sinusoidal signal. The transducer produces *two* ultrasonic beams, one at each frequency, of about the same spatial extent. The zone where both beams have high intensity is shown as an elongate oval.

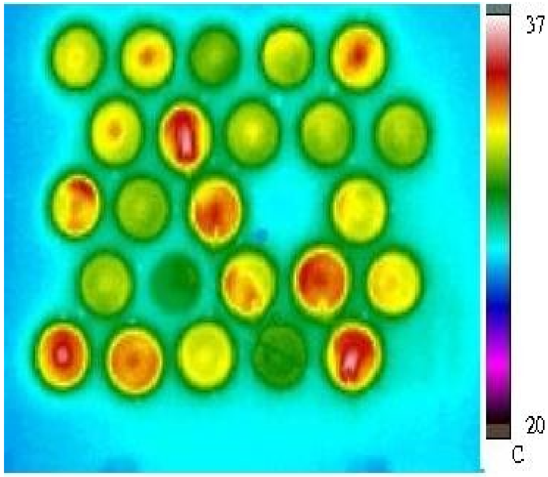


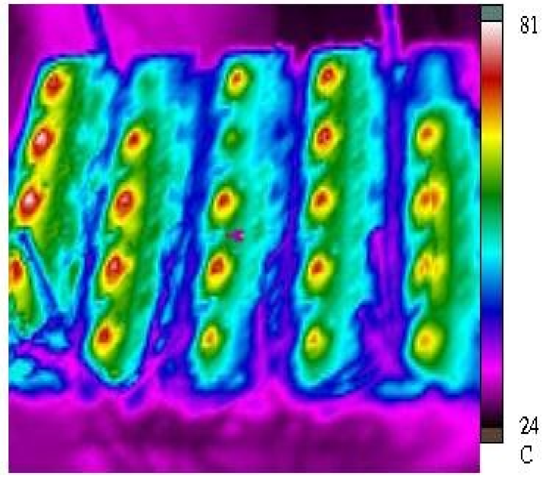
So far we simply have two superimposed ultrasonic signals. The magic occurs when the signals are strong enough that propagation in the interaction zone is *non-linear*. When this happens additional signals comprising the sum and difference of the harmonics of the driving signals are generated. It turns out that the strongest, and the one of most interest to us, is the signal at the difference frequency; in this case, 500 Hz. This low-frequency energy is generated throughout the interaction volume and it happens to have precisely the phase distribution needed to function as an end-fire array down the axis of the interaction zone. The result of all this, then, is that a physically compact source element, the ceramic transducer, can generate a focused low-frequency beam that would otherwise require a much larger source element.

The principal downside of the parametric array process is its inefficiency. We need both a large interaction zone, for directivity, and strong difference-frequency generation to have a useful system. These requirements drive us to pump as much power as practicable into the ultrasonic driving signals.

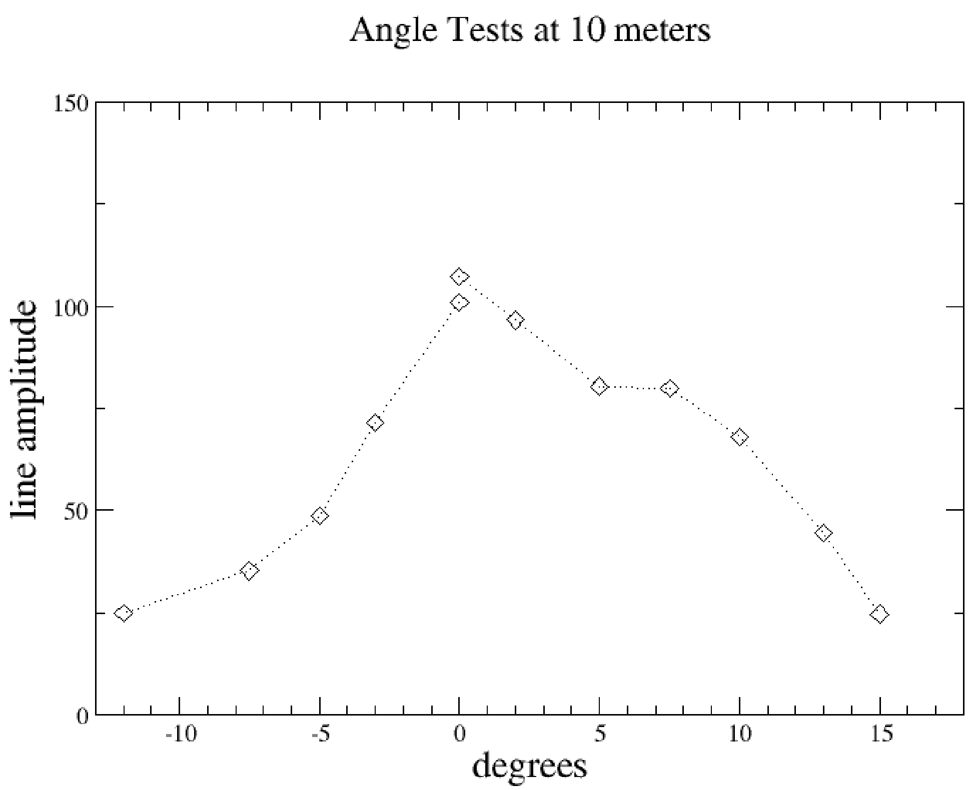
In the system we developed, we chose to implement an array of 25 medium-power (Airmar AR41) transducers, each driven by a separate amplifier. Below are photos of the final system during outdoor testing. The amplifier bank is mounted behind the transducer array and the power control unit is on the lower level of the carrier.

In initial field tests, the system drew about 3 kW from the power mains. To check the performance of individual elements we took thermal images (below) of the transducer array (left) and the amplifier banks (right). Note, for example, that one transducer and its associated amplifier show no heating during operation. In this instance we discovered that the transducer had burned out and replaced it.

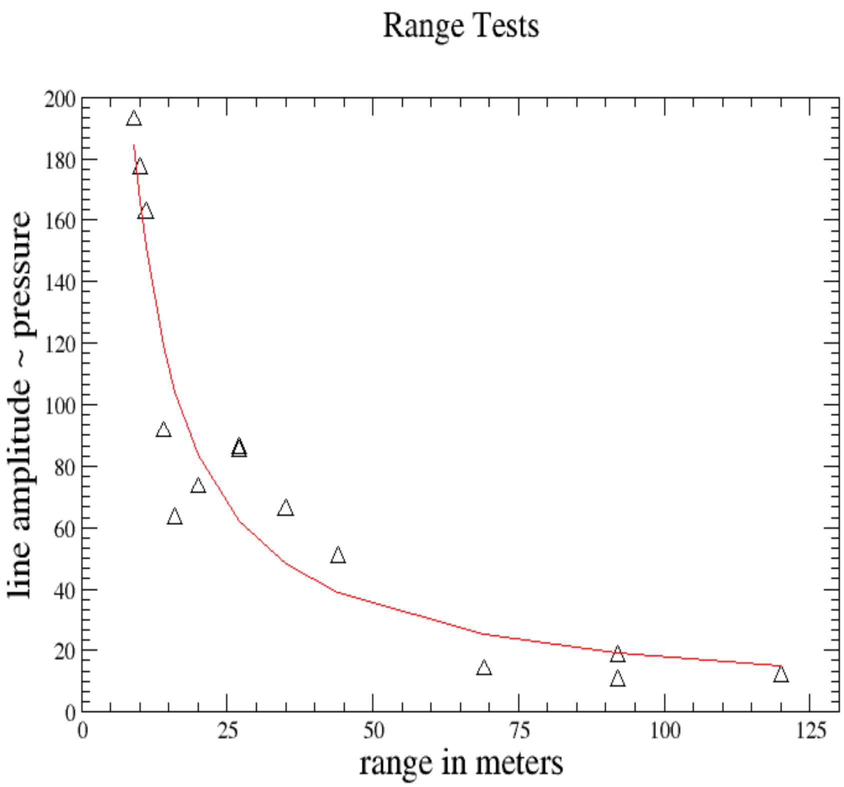




The next figure shows the angular dependence of received signal amplitude of a 1 kHz signal at a range of 10 meters. (These measurements and the subsequent ones are corrupted by high levels of ambient mechanical noise during the field test.) We estimate the half-power beam-width to be roughly 10 degrees.



The next figure shows amplitude versus range for a 1 kHz signal. The test site was a large quad at Colorado School of Mines and the irregularities in signal decay with range reflect, we believe, both ambient noise and multipathing.



Summary

We have constructed a parametric array, of approximately 3 kW input power, which provides a collimated beam of low-frequency sound from a (relatively) physically compact device. Preliminary field tests verify that the array is functioning as theory predicts.

Bibliography

Sonar Systems by James E. Barger, in **Handbook of Acoustics**, Malcolm J. Crocker ed., John Wiley & Sons, 1998.