Title
FAST ULTRASONIC IMAGING IN A LIQUID FILLED PIPE

Authors
Kolbe, W.F.
Turko, B.T.
Leskovar, B.

Publication Date
1985-10-01

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

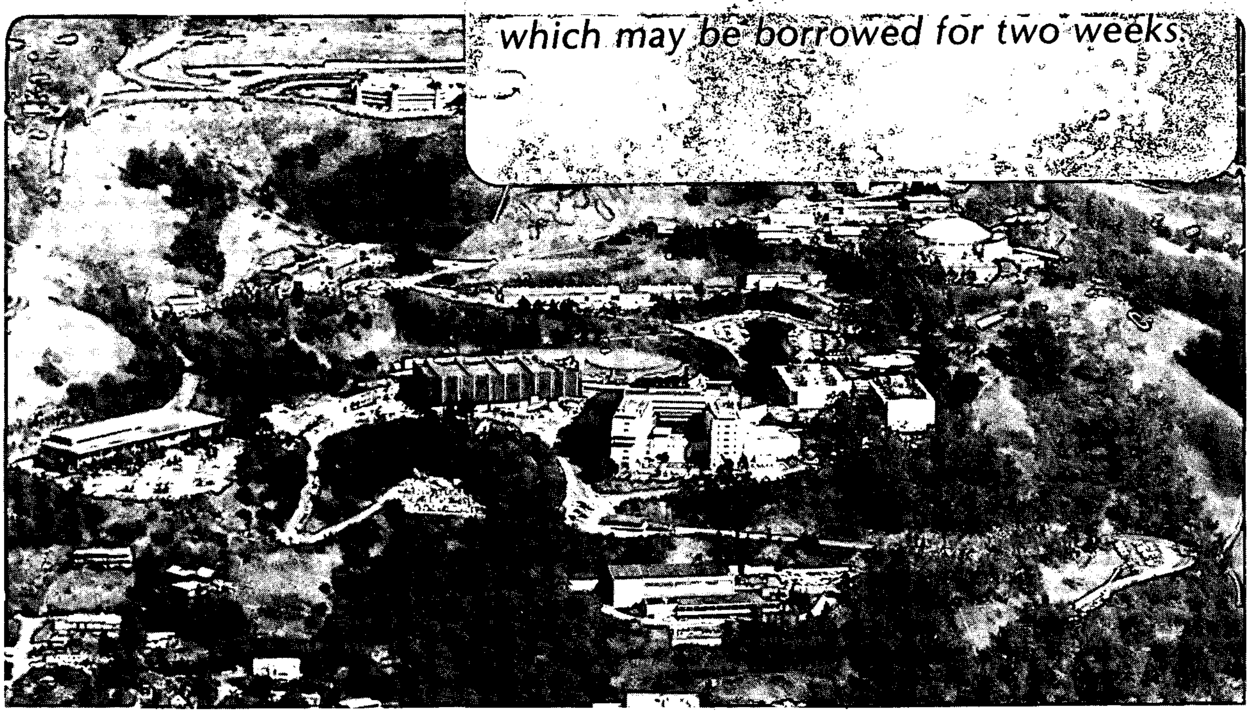
Engineering Division

Presented at the IEEE Nuclear Science
Symposium, San Francisco, CA,
October 23-25, 1985

FAST ULTRASONIC IMAGING IN A LIQUID FILLED PIPE

W.F. Kolbe, B.T. Turko, and B. Leskovar

October 1985



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

FAST ULTRASONIC IMAGING IN A LIQUID FILLED PIPE

LBL-19207

W.F. Kolbe, B.T. Turko and B. Leskovar

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720 U.S.A.

ABSTRACT

A new method is described for the imaging of the interior of a liquid filled metallic pipe using acoustical techniques. The experimental system incorporates an array of 20 acoustical transducers and is capable of capturing the images of moving bubbles at a frame rate in excess of 300/s. The transducers are mounted circumferentially around the pipe. Each transducer is pulsed in sequence, and the echoes reflected from vapor bubbles in the interior are detected, digitized and processed by a computer to generate an image. The high rate of speed was achieved by the use of newly developed software and electronic circuitry. This approach has eliminated most of the spurious echo signals which degraded the performance of previous imaging systems. The capability of the method is illustrated by imaging actual vapor bubbles in rapid sequence in the pipe.

INTRODUCTION

In nuclear power reactor systems it is essential that a continuous flow of water or liquid sodium coolant be maintained on the walls of the heat exchanger used to extract the thermal energy. Because of the danger of dryout in these systems, it would be very desirable to be able to observe the presence of vapor bubbles and liquid film flow within the cooling structures. Since the heat exchangers are made of metal and operate under hostile environmental conditions, it is not normally feasible to provide windows or other means which will permit optical viewing of the interior conditions.

A number of methods[1,2] have been developed for use in reactor safety research facilities to investigate the two-phase flow conditions which are frequently present. For opaque systems, the methods used include conductivity and capacitance probes, thermocouples, flow-meters of various types, and gamma ray and flash x-ray absorption techniques. In transparent model systems, direct optical viewing with TV or other cameras has been employed. The present authors have developed[3-6] an electro-optical system for the imaging and computer analysis of two-phase flow parameters in such model systems. Although the above methods have been an effective tool for reactor safety research, there is a need for non-intrusive measurements of two-phase flow phenomena through optically non-transparent media.

Our preliminary investigations[7,8] showed that acoustic techniques offer promise for imaging through optically non-transparent media. Acoustic imaging uses ultrasonic waves to probe a sample volume and produce signals that can be converted into visual images of its internal structure. Acoustic imaging techniques have been developed[9-11] in recent years for use in medical diagnosis, nondestructive testing, microscopy, underwater imaging and seismic exploration. To our knowledge, acoustic methods have not been used for the imaging of fluids in piping structures, although Lynnworth et al[12] have reviewed other uses of ultrasonic techniques in nuclear reactor applications.

In a recent paper[8], the results of our preliminary study of the feasibility of applying acoustic techniques to the problem of imaging the interior of a metallic pipe were described. Measurements were reported showing the echo signals produced by air filled glass spheres of various sizes positioned in an aqueous medium within the pipe. The influence of the pipe wall thickness and material on the amplitude of the echo signals was also investigated.

With the apparatus described previously[8], the electronic system used was able to capture and display only a single frame at a time. This work has now been extended and we report here the results obtained on an improved ultrasonic imaging system capable of pulsing and decoding in real time the echo signals of actual moving vapor bubbles in the pipe. High frame rates of up to 500/s have been achieved with the use of a newly designed digitizer which preprocesses the echo data on-the-fly to remove spurious echo signals. This apparatus is described in greater detail in Ref. 13.

EXPERIMENTAL APPARATUS

Transducer Mounting Arrangement

A simplified block diagram of the experimental apparatus used for the acoustic imaging is shown in Fig. 1. An array of 20 acoustical transducers is mounted around the perimeter of a stainless steel pipe, inner diameter 57.5 mm and wall thickness 3 mm. The pipe is sealed at the bottom and filled with water to a depth sufficient to cover the transducer plane. For imaging purposes, air under low pressure is injected at the bottom of the pipe by a variable speed rotary peristaltic pump. Long bursts of air bubbles of various sizes are formed which rise at random to the surface.

In order to couple the acoustic energy into the pipe, flat mounting surfaces are machined on the pipe surface at 18° intervals. An acoustic coupling fluid (mineral oil) is used between each transducer and the pipe to provide an intimate contact. Because the acoustic impedance of steel is much larger than that of water, most of the acoustic energy is reflected back to the transducer from the steel-water interface. The result is a persistent reverberation signal between the two walls of the pipe which can obscure the desired echoes from the interior of the pipe. To overcome the effect of these spurious echoes the flat surfaces on the pipe are machined at a small angle with respect to the normal to the surface. When this is done[8], the reverberation echoes follow a zig-zag path along the length of the pipe and are not returned to the transducer. As a result, the effects of reverberation are significantly reduced. Further reduction of the reverberation echoes is achieved by wrapping the lower portion of the pipe with a damping (duxseal) material. For the tilt angle of 10° used, the acoustic beam in the water is inclined by only 2.5° because of refraction at the metal-water interface.

The tranducers used (Panametrics, Inc. Mod. V112), are constructed from lead niobate disks 6 mm in diameter, resonant at 10 MHz, and heavily damped to permit the generation of acoustic pulses of a few hundred nanoseconds in width. The acoustic energy is radiated from the face of each transducer in a narrow beam of a diameter approx. equal to the transducer diameter.

Data Acquisition and Processing

The data processing system consists of a PDP 11/34 computer and associated peripherals, including a multiple magnetic disk drive, VT-100 terminal, printer and Tektronix model 4012 graphics terminal to display the bubble images. A Borer model 1533B crate controller is used to interface the CAMAC imaging modules to the computer bus.

As described in Ref. 13, when the imaging module is triggered, a sequence is initiated in which each of the 20 transducers is pulsed in turn thereby generating a series of acoustic pulses within the pipe. The echo pulses produced by bubbles in the pipe are pre-processed as they are detected by comparing their arrival times with event flags stored in a mask memory located in the module. Only those echoes which are not marked for deletion in the mask are passed to the data processing system. In addition, an adjustable dead-time is provided to reject closely spaced echo bursts which can be produced by strong reflections. When the mask is properly loaded, most of the spurious echoes resulting from reverberations of the acoustic pulse passing through the pipe wall can be eliminated. As a result, the amount of data which must be processed by the computer is significantly reduced.

Echo data not rejected by the mask and other circuitry is passed to a derandomizing FIFO memory before transfer to the computer. When data is present in the FIFO, a look-at-me (LAM) signal is generated which triggers an interrupt service routine. This routine is written in assembly language to maximize the transfer rate of data to the computer. The data is stored in the computer in a circular buffer capable of holding up to 2000 events with the current position in the buffer maintained by a pointer.

Prior to the actual collection of bubble data by the system, the rejection mask memory must be loaded with the appropriate bit pattern. Several operator commands are provided to accomplish this. The command, LMASK, causes all the detected echoes from a single frame to be stored directly in the mask. When this is done with the pipe full of water and free of bubbles, a pattern is produced which effectively eliminates all spurious echoes produced by reverberations in the pipe wall. In order to eliminate the effects of small drifts in the position of the spurious echoes, the mask can be augmented by the command AUGMASK to set the bits representing channels on either side of the bits previously set by LMASK. A command, PADMASK is provided to block out larger regions of the mask memory in which the desired bubble echoes are not expected. Finally, the current contents of the mask can be displayed on the terminal with the command, SHOMASK.

After the detection and storage in the computer memory of a number of echoes from bubbles in the pipe, the data can be processed to generate and display images of the pipe interior. This is done by converting the transducer angular positions and echo arrival times to X-Y coordinates suitable for plotting.

While the transformation of a single frame to plotting coordinates requires only a fraction of a second, the display and inspection of each frame is rather time consuming. For this reason additional parameters are provided to skip over frames containing less than a preset number of echo events and to restrict the number of accepted echoes per transducer to a preset value. In this way large numbers of frames containing no useful echoes can be rapidly processed without operator intervention.

Except for the interrupt service routine, all the software to control the imaging system is written in FORTRAN. The program is somewhat unusual in that all subroutine calls and parameter inputs are provided through command strings input from the terminal. These strings are parsed into individual commands by the system which supplies them one at a time as needed to maintain the program flow. When the command buffer becomes empty, an appropriate prompt is provided to the user to inform him that a command is needed. A number of commands can be placed in a disk file and called repeatedly as an indirect command file.

EXPERIMENTAL RESULTS

As described in the previous section, the application of a trigger pulse to the imaging module initiates a sequence in which each of the 20 transducers is pulsed in turn after which the echo data received is digitized. The timing of the system is controlled by a master clock. Since all echoes of interest occur between the walls of the pipe, the clock frequency is adjusted[8] to make the time between successive transducer pulses equal to twice the transit time of the acoustic wave across the pipe diameter. For the present pipe diameter of 57.5 mm, this time is about 76 μs, making the total time for a complete 20 transducer frame equal to 1.5 ms. Thus aside from data acquisition overhead by the computer, a maximum frame rate of 670 frames/s is possible.

The interrupt service routine (ISR) is able to read and store the FIFO data and maintain the buffer pointers at a rate of about 40 μs per event after an initial latency of 250 μs for the ISR to be serviced. Since the ISR is called as soon as the first event is available to the FIFO, data storage in the computer occurs simultaneously with data generation and is completed shortly after the end of the frame. Measurements of the echo signals generated by air bubbles in the pipe have been made at frame rates up to 500 frames/s with the present apparatus without interrupt overrun, although most of the data to be described below was acquired at a rate of about 300 frames/s.

Imaging of Phantom Bubbles

In order to demonstrate the operation of the imaging apparatus, a thin walled glass sphere of diameter 14.8 mm was positioned in the water filled pipe with its center in the transducer plane and its horizontal position at the pipe center. A single scan of the 20 transducer array was triggered to capture the echo data which was then decoded as described above. Figure 2 shows the images obtained under various conditions. In these and the photographs to follow, the echo locations are denoted by small crosses and the outline of the steel pipe is shown by a pair of dotted circles.

In Fig. 2(a) the mask memory was purposely loaded with zero values at all addresses thereby permitting the transfer of all the discriminated echoes to the computer. The resulting image shows not only the bubble itself but also a number of spurious echoes near the wall of the pipe. These echoes are a result[8] of the reverberation caused by the acoustic pulse as it traverses the large acoustic impedance discontinuity at the metal-water interface. Since these reverberation echoes are of no use in a typical imaging application, obviously they should be eliminated, both to reduce processing time and to minimize computer memory storage requirements.

The image in 2(b) was obtained by temporarily removing the bubble and generating a mask (with the command LMASK) prior to the actual generation of the bubble image. Since the spurious reverberation echoes are almost constant and independent of the bubble positioning, placing them in the mask effectively eliminates them. As seen from the figure, of the approximately 60 spurious echoes in (a), only 2 remain. The appearance of the latter is a result of small drifts in the system, causing the echoes to appear in channels adjacent to those blanked by the mask. In Fig. 2(c) the same mask was augmented as described above to place additional blanking in adjacent channels. The resulting image now contains no spurious points.

Although all the spurious echoes have been removed, the image of the bubble still contains, at most angular positions, more than one echo. This is another manifestation of the reverberation produced at the front wall of the pipe; the acoustic signal emanating from the surface of the pipe consists of not one but several closely spaced pulses, each of which is reflected from the bubble. With the software available, the appearance of the image can easily be improved. Figure 2(d) shows the result when only one echo per transducer is transferred to the plotting buffer. The image in this form would be most useful as input data for further data reduction and image analysis.

With the bubble centered on the axis, echo signals are produced at all angular positions. Because of the specular nature of the reflections, as the bubble is moved off axis only a fraction of the echos can be detected. This is illustrated in Fig. 3 where a series of exposures of the same bubble at positions (0,0), (-2,2), (-4,4) and (-6,6) mm is shown. While only a few points remain for bubbles far from the center of the pipe, they lie at opposite sides and still permit an estimate of the bubble diameter to be made.

When the bubble is moved in the vertical direction, a similar loss in echo amplitude results. Figure 4 shows the result of imaging a bubble at positions (a) 3 mm above the transducer plane, (b) in the plane and (c) 3 mm below the plane. In each case the apparent diameter detected is the major diameter of the bubble; only the intensity and hence the number of detected echoes changes. This property of the imaging process can be exploited in the case of moving bubbles by superimposing the individual image frames produced as the bubble moves through the transducer plane. The effective range over which the bubble is detected is about 6 mm, a distance approximately equal to the diameter of the transducer element used.

Imaging of Moving Air Bubbles

Air bubbles were generated in the water filled pipe by introducing a flow of air at the bottom of the pipe (described above), using a plastic hose attached to a peristaltic pump. By adjusting the orientation of the hose and the air flow rate, some control of the size and number of bubbles produced could be obtained. Images of a series of bubbles were then generated by pulsing the imaging module at a fixed rate (300 frames/s) and storing the echoes produced in the computer. The mask and decoding parameters were adjusted to reject most frames in which there were no bubbles present. The remaining frames were then decoded and displayed on the graphics terminal.

A typical sequence of decoded images consisted of numbers of empty frames which were bypassed by the software, followed by groups of adjacent frames containing images which could be recognized as due to a bubble passing through the image plane. Figure 5 (a) to (e) shows a series of images (frame numbers 313 through 317) produced by a passing bubble. While the general form of the image is the same in each frame, it can be seen that the detailed shape of the bubble is changing during the sequence. This is not surprising since a visual inspection of the bubbles shows that they are vibrating and changing shape as they rise through the water. By superimposing all of the above frames, an improved representation of the bubble can be obtained as shown in (f).

A number of example bubble images are shown in Fig. 6. In each case the image consists of a superposition of all the individual frames containing the bubble. The number of frames/image ranges from only 2 for a particularly small bubble such as shown in (b) to 6 for the more complex pattern shown in (d). An example of a bubble moving with a significant transverse velocity is shown in (f) in which the image in each successive frame was found to lie further away from the pipe center.

The longitudinal velocity of the bubbles along the pipe axis can be estimated from the known frame rate of 300 frames/s and the distance, determined above, of 6 mm over which a typical bubble can be detected. Since a typical bubble image persists for about 4 frames, the average bubble velocity across the image plane is approximately 450 mm/s.

DISCUSSION

A new acoustic imaging method for the real-time detection of air bubbles within a steel pipe has been described. With this method, it has been demonstrated that it is possible to capture the images of moving bubbles at frame rates in excess of 300/s. This high rate of speed was achieved by the use of improved software and specially developed[13] electronic circuitry. A major improvement resulted from the use of a presetable "frame mask memory". This was shown to eliminate most of the fixed spurious echo signals which degraded the performance of our previous[8] imaging systems. The quality of the bubble images produced was surprisingly good considering the limited resolution of the 20 transducer array employed.

In the present system the 20 transducers in the array are pulsed in series, thus the pipe diameter and the velocity of sound in the water limit the minimum frame time to 1.5 ms. The maximum frame rate cannot therefore exceed about 650 frames/s irrespective of the processing time. We have seen that the quality of the bubble images can be significantly enhanced by superimposing the data from several frames each containing the same bubble. This is possible only if the bubble is moving rather slowly. Velocities greater than a few m/s would, with the present system, produce images of poor quality.

The key to achieving greater resolution is, of course, to increase the number of elements in the imaging array. If this were done and a purely serial readout were employed, the frame time would be even longer than it is in the present system. Therefore it would be necessary to develop a serial-parallel readout mode in order to speed up the system response. The transducer arrays, forming one or more parallel rings around the pipe, would be divided into groups. The groups would be fired simultaneously, but the individual transducers in each group would be pulsed in sequence.

A number of enhancements to the computer software would be required to process the high resolution images obtained with this improved system. A correlation technique could be employed to compare the images from different frames thereby further eliminating extraneous echoes and improving image quality. If 2 or more rings of transducers are used, a similar technique can be used to enhance resolution and determine bubble velocity distributions. Finally, it would be very useful to employ feature analysis techniques to determine bubble diameter, shape and volume statistics from the collected data.

ACKNOWLEDGMENTS

This work was performed as part of the program of the Electronics Research and Development Group of the Department of Instrument Science and Engineering of the Lawrence Berkeley Laboratory, and supported by the U.S. Department of Energy under contract No. DE-AC03-76SF00098. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

REFERENCES

1. G.F. Brockett and R.T. Johnson, Single-Phase and Two-Phase Flow Measurement Techniques for Reactor Safety Studies, Electric Power Research Institute Topical Report, RP-694-1, NP-195 (1976).

2. G.F. Hewitt, Measurement of Two-Phase Flow Parameters, Academic Press, (1978).

3. B. Leskovar, B.T. Turko, W.F. Kolbe and R.K. Sun, Development of Electro-Optical Instrumentation for Annular Two-Phase Flow Studies, Electric Power Research Institute Topical Report, RP-1379-01, NP-1831 (1981).

4. B. Leskovar, R.K. Sun, W.F. Kolbe and B.T. Turko, Measurement of the Thickness of Liquid Film by Means of the Capacitance Method, Electric Power Research Institute Topical Report, RP-1379-1, NP-1212, (1979).

5. B.T. Turko, W.F. Kolbe, B. Leskovar and R.K. Sun, Development of Electro-Optical Instrumentation for Reactor Safety Studies, IEEE Trans. Nucl. Sci., NS-28, No. 1, 728-739 (1981).

6. R.K. Sun, W.F. Kolbe, B. Leskovar and B.T. Turko, Measurement of Thickness of Thin Water Film in Two-Phase Flow by Capacitance Method, IEEE Trans. Nucl. Sci., NS-29, No. 1, 688-694 (1982).

7. W.F. Kolbe, B.T. Turko and B. Leskovar, Acoustic Imaging of Vapor Bubbles through Optically Non-Transparent Media, IEEE Trans. Nucl. Sci., NS-31, No. 1, 726-732 (1984).

8. W.F. Kolbe, B.T. Turko and B. Leskovar, Acoustic Imaging in a Water-Filled Metallic Pipe, IEEE Trans. Nucl. Sci., NS-32, No. 1, 1016-1024 (1985).

9. Proceedings of the IEEE, Special Issue on Acoustic Imaging, 67, No. 4, (1979).

10. P.N.T. Wells, Ed., Ultrasonics in Clinical Diagnostics, Longman Group, Ltd. (1977).

11. R.A. Lemons and C.F. Quate, Acoustic Microscopy, in Physical Acoustics, Principles and Methods, 14, 1-92, W.P. Mason, Ed., Academic Press (1979).

12. L.C. Lynnworth, F.P. Papadakis, D.R. Patch, K.A. Fowler and R.L. Shepard, Nuclear Reactor Applications of New Ultrasonic Transducers, IEEE Trans. Nucl. Sci., NS-18, 351-362 (1971).

13. B.T. Turko, W.F. Kolbe and B. Leskovar, Ultrasonic System for Imaging of Vapor Bubbles in a Liquid Filled Pipe, LBL Report, LBL-19208 (1985).

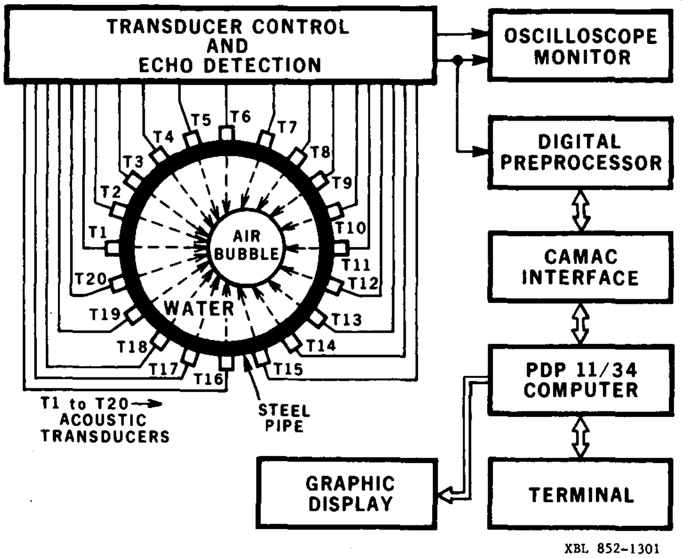


Fig. 1 General block diagram of the acoustic imaging system.

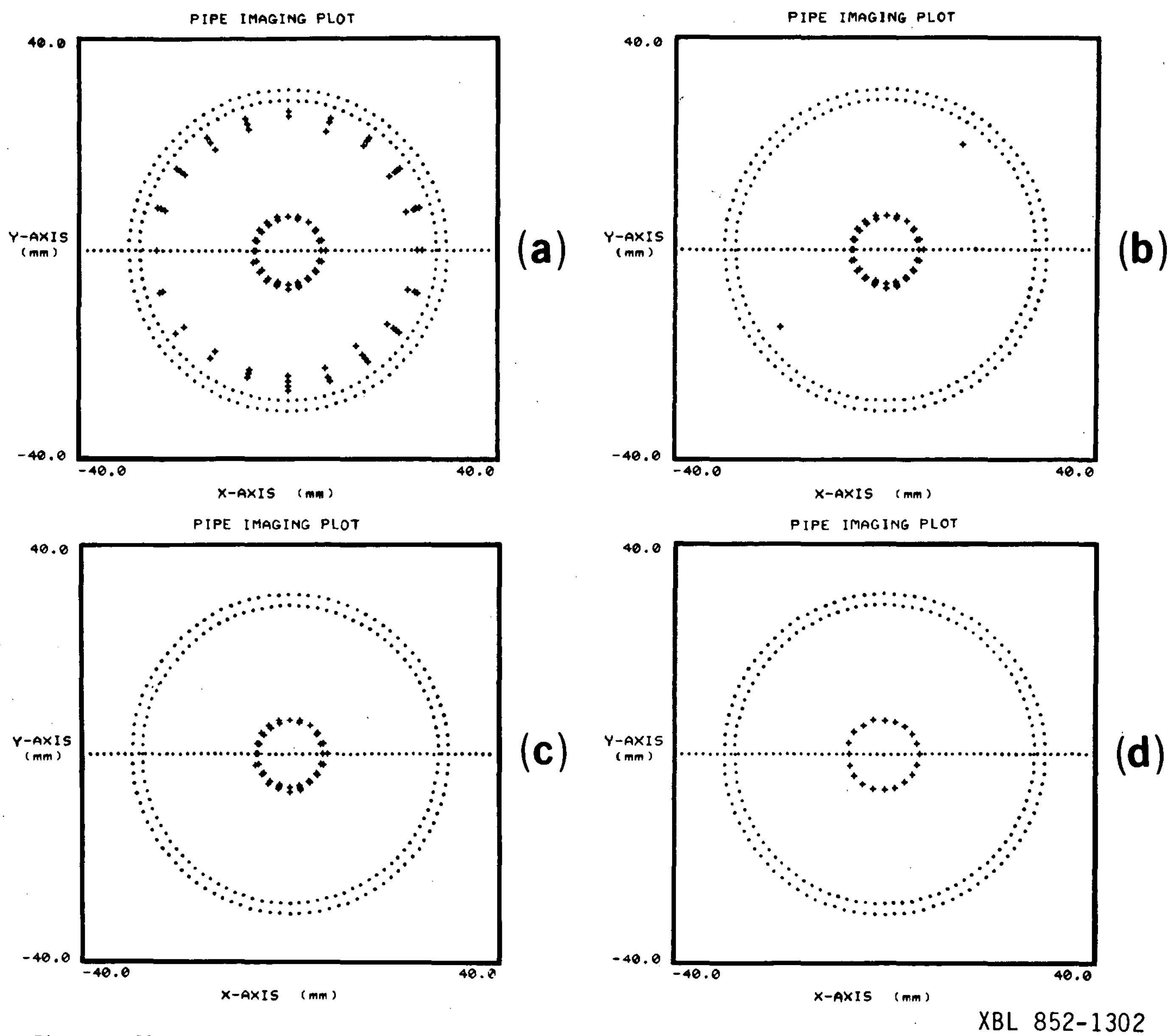
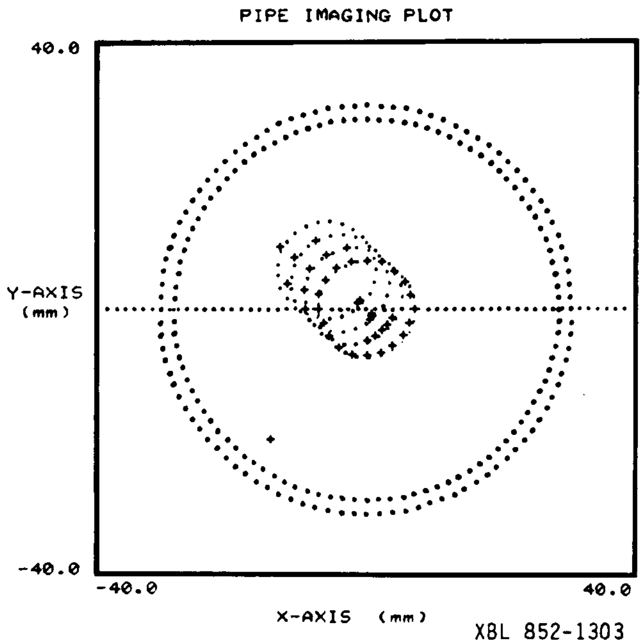
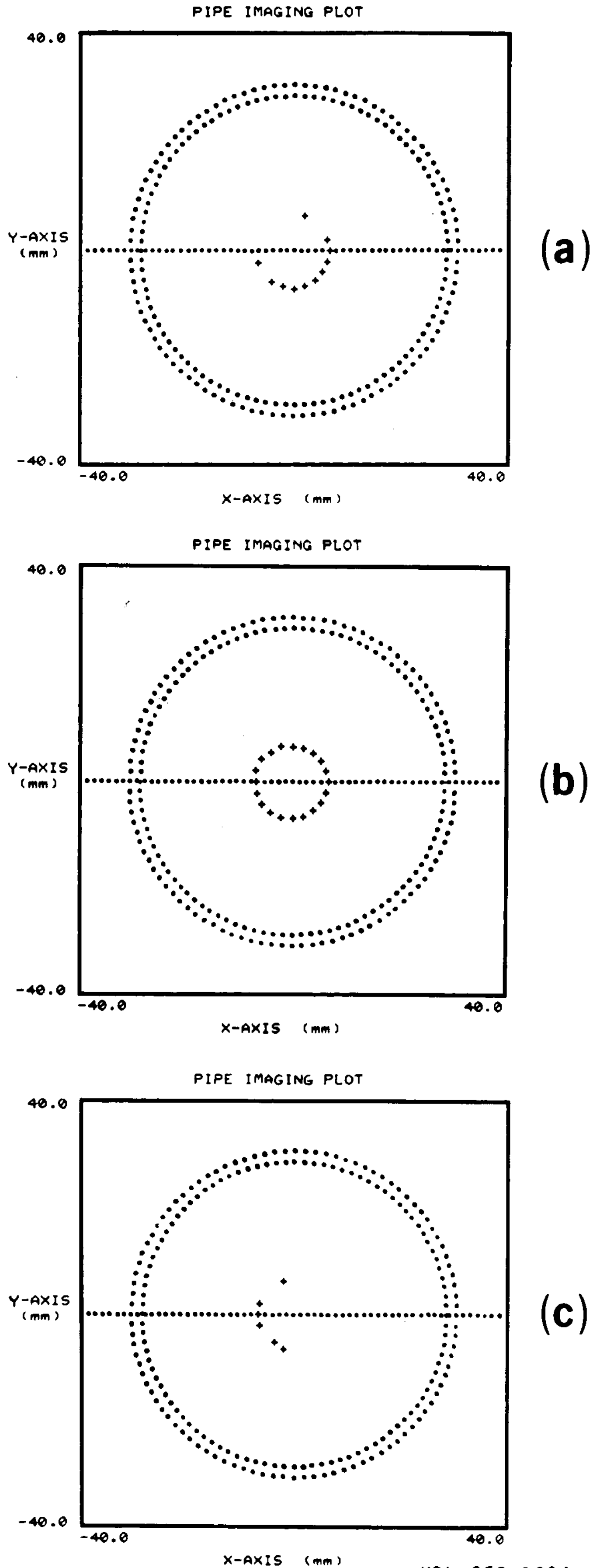


Fig. 2 Illustration of data reduction techniques in the imaging of spherical bubbles. (a) without use of mask, (b) mask loaded with background echoes, (c) augmented mask and (d) total echo count restricted.



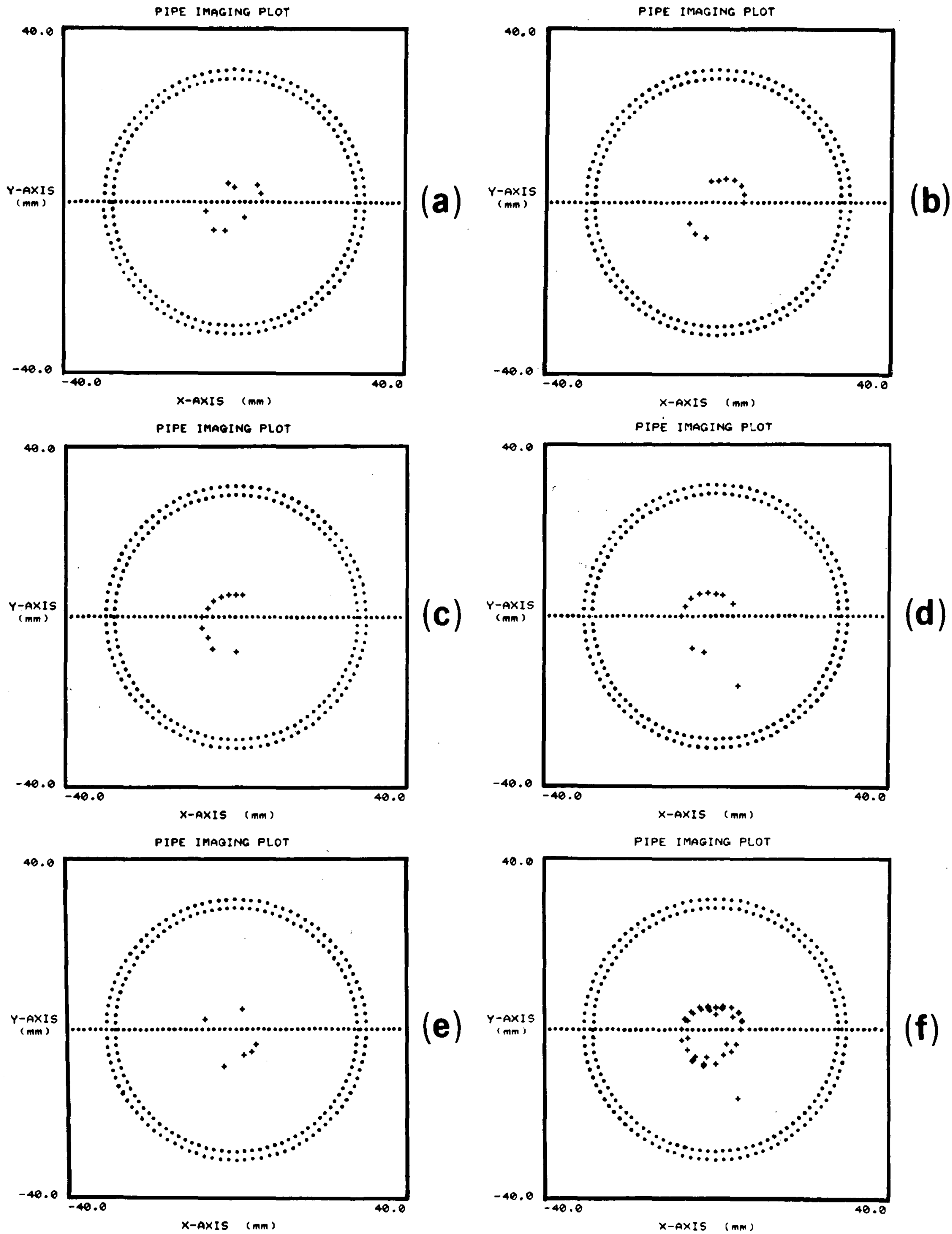
XBL 852-1303

Fig. 3 Images of spherical bubbles positioned at differing transverse locations.



XBL 852-1304

Fig. 4 Illustration of the effect of vertical position on spherical bubble image. (a) 3mm above plane, (b) centered in transducer plane and (c) 3 mm below plane.



XBL 852-1305

Fig. 5 Images of an air bubble passing through the transducer plane. (a) through (e) individual images from successive frames and (f) superposition of the above.

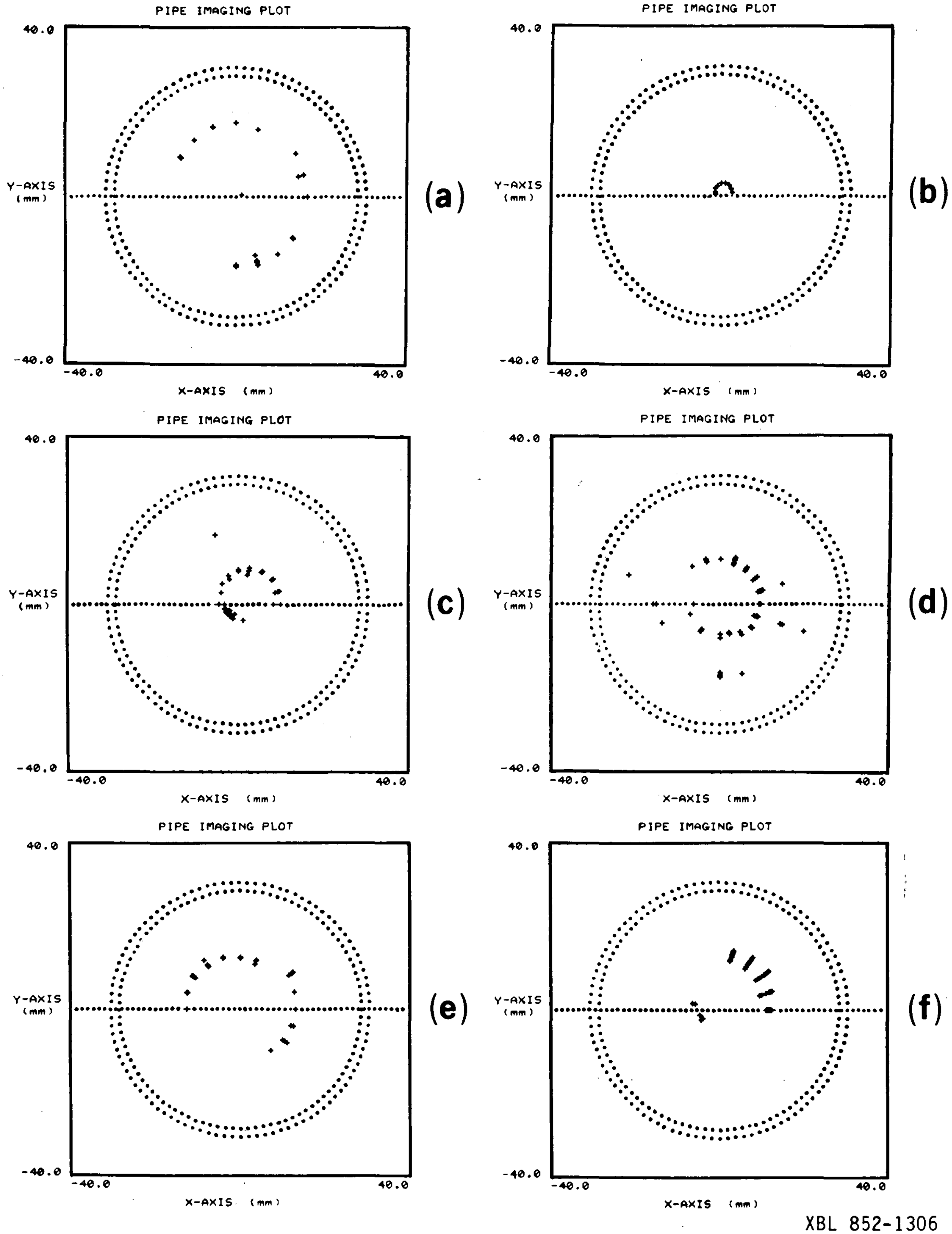


Fig. 6 Sample images of a number of air bubbles.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720