BUBBLE ACOUSTICS: FROM WHALES TO OTHER WORLDS

TG Leighton Institute of Sound and Vibration Research, Faculty of Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK

1 INTRODUCTION

Gas bubbles in liquids have an extraordinary ability to interact with sound fields. They are potent generators, absorbers, and scatterers of sound, and can have a profound effect upon the sound speed (changing it on subsecond timescales by a factor of 2 or more under breaking ocean waves, for example). Bubbles generate the song of a babbling brook, and ocean sounds that help us understand the global carbon budget. Bubbles activated by ultrasound can assist industrial processing, or aid medical diagnosis and therapy. This Rayleigh Medal Lecture paper records the work I have undertaken to understand and exploit them.

2 BUBBLES IN WATERFALLS AND THE UPPER SEA SURFACE

Figure 1 shows the simultaneous hydrophone record [panel (a)] and high speed video [panels (b) to (h)] recorded when a water drop impacts upon a body of water. This process is familiar for images resembling those in the final frame [panel (h)], where the half-submerged lens clearly reveals the water jet that rises into the air as, below it, the crater shrinks in the water surface. This image is associated with the famous ‘plink’ of a dripping tap.

That ‘plink’ can be seen as the exponentially decaying sinusoid in the hydrophone trace of panel (a), the labelling indicating that it is synchronous with panel (f).

Therefore the famous ‘plink’ sound is not caused by either the jet or the crater, but by the tiny bubble that was pinched off from the base of the closing crater [panels (e) to (g)].

This experiment illustrates how powerful an acoustical entity is a gas bubble in liquid. Each bubble behaves like an underwater bell, small ones producing plinks of high notes, and larger ones generating low notes[1]. Therefore from the pitch of the ‘plink’, one can determine the size of the bubble.

The first count of the size distribution of bubbles[2] entrained in the natural world, made using the sounds they generated, was undertaken in the early 1980s. The data were taken at Kinder Scout in the Peak District, in streams and waterfalls [Figure 2(a)]. This led to similar counts for the bubbles trapped by rainfall over the ocean[3,4], and today we see the deployment of at-sea acoustic monitors[5] for rainfall (Figure 2(b)). Whilst satellite data of rainfall over land masses can readily be ground-truthed by weather stations, it is not so simple at sea: islands and ships [which predominantly cover particular regions of the Northern Hemisphere – Figure 2(c)] can have atypical local conditions unsuitable for the large-scale ground-truthing of satellite data, so that free floating acoustic buoys were developed to monitor rainfall far from land through the sound it generates [Figure 2(b)].

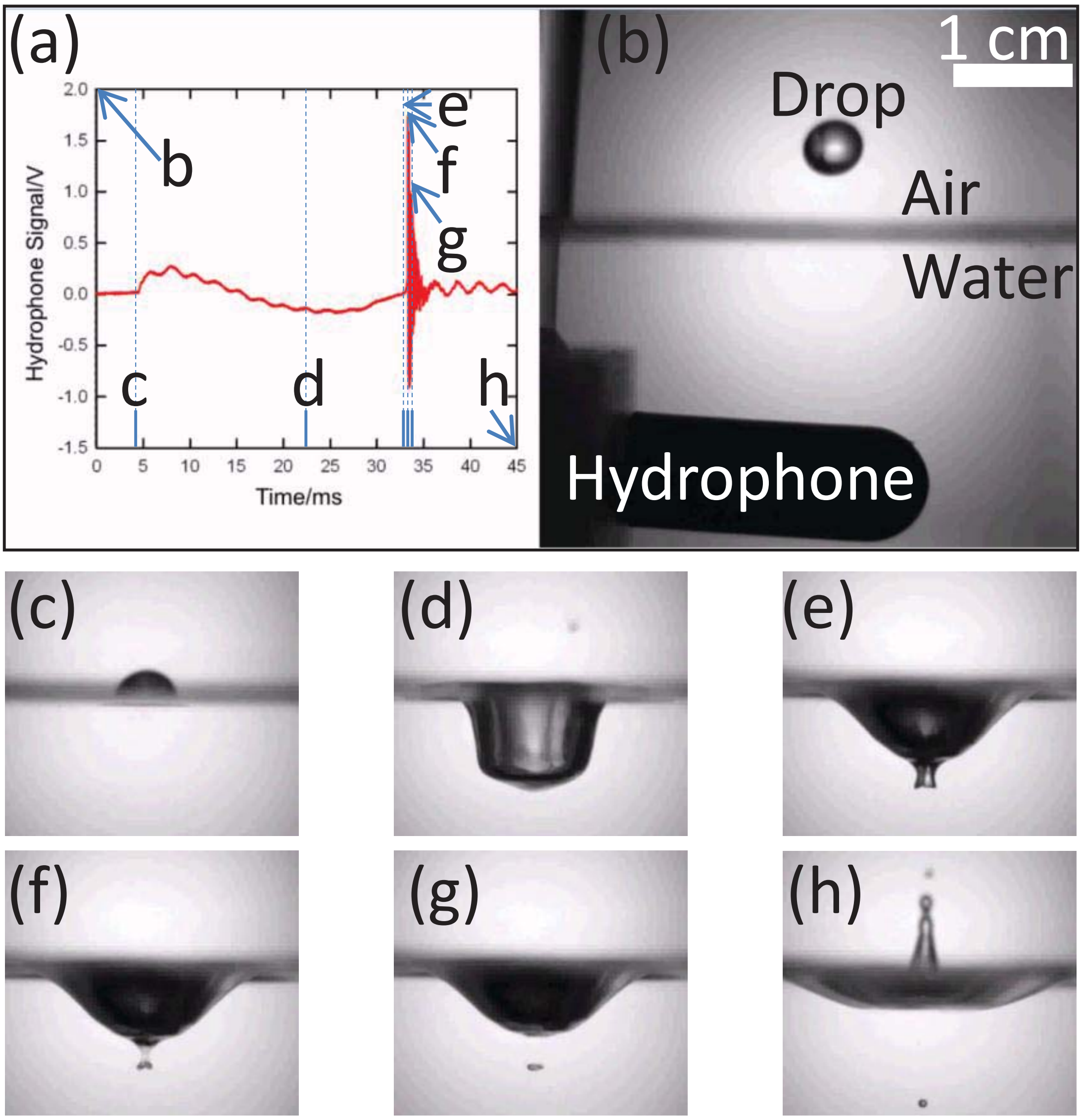
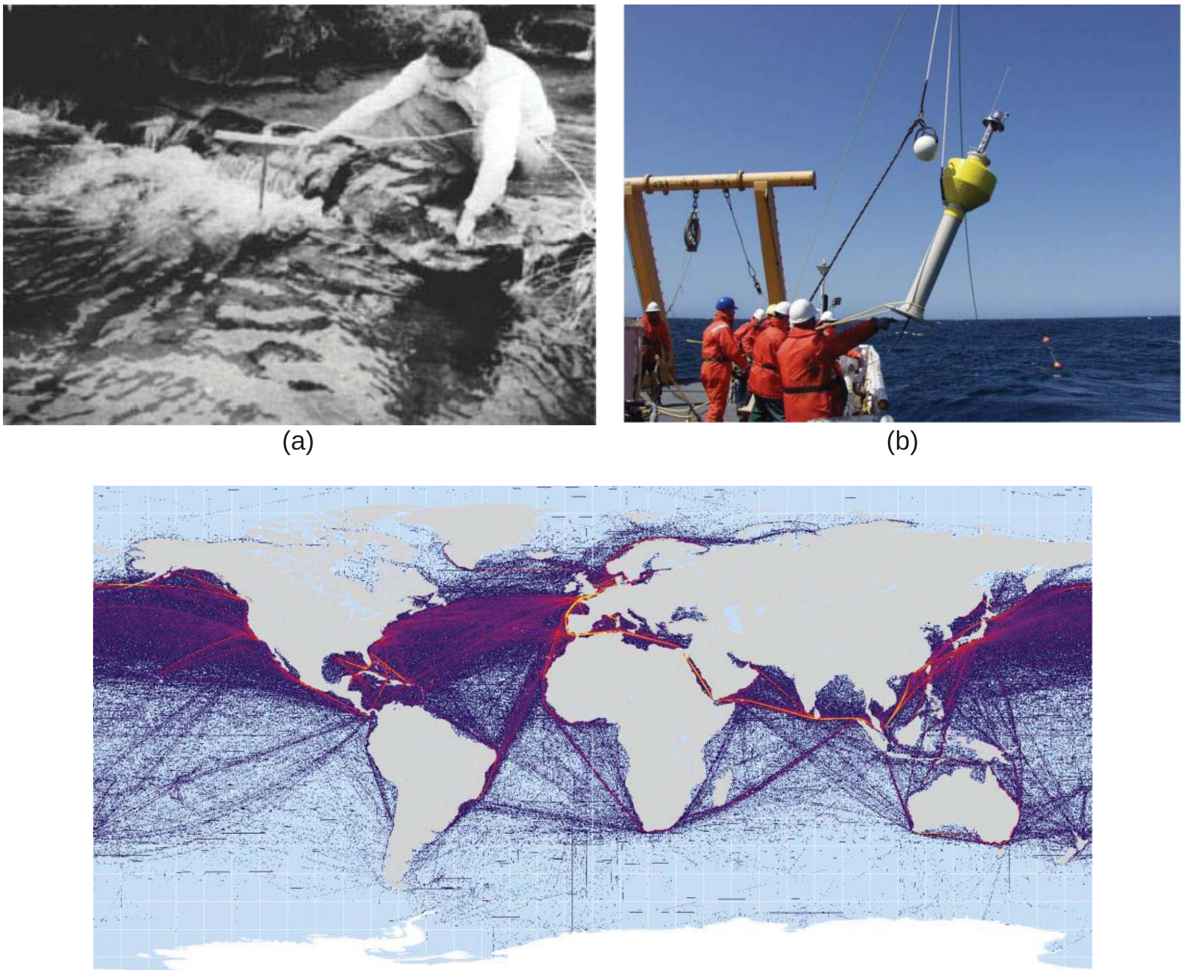


Figure 1. (a) The hydrophone output (in red, with the timing of subsequent frames labelled (b)-(h) showing the impact of a water drop falling from air into water. The hydrophone signal from (c) to (d) is hydrodynamic, the only significant acoustic emission occurring when a small bubble is pinched off from the base of the crater ((e)-(g)).



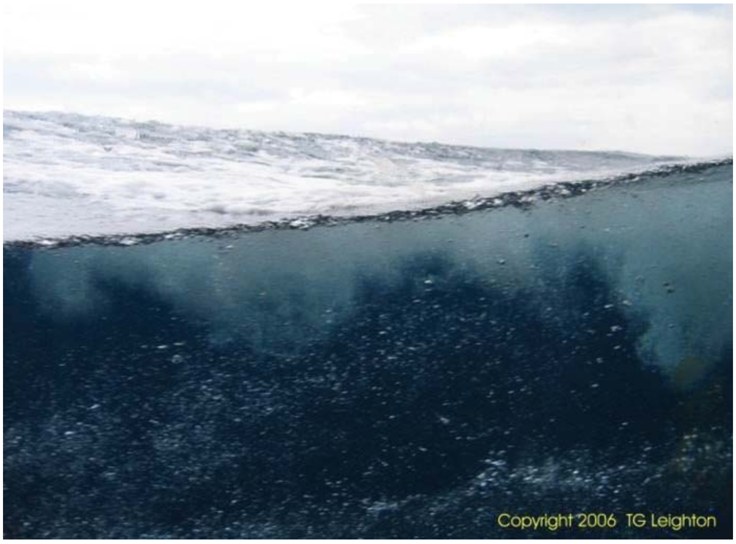
(a) (b)

(c)

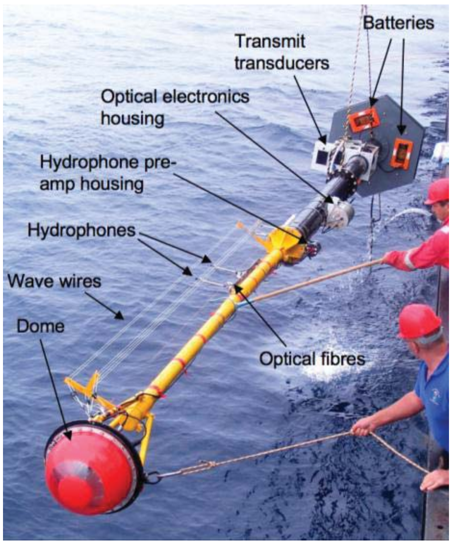
Figure 2. (a) The author lowering a hydrophone into a stream in data in Kinder Scout to take the first bubble size distribution and count in the natural world using the passive acoustic emissions from bubbles. [2]. (b) Deployment of Mk IV acoustic Rain Gauge (ARG) from CFAV Quest[6] (Photo courtesy D. Hutt). (c) Map showing shipping lanes[7].

The technique was also deployed in the ocean[8-10] to detect bubbles trapped under breaking sea waves. When an ocean wave breaks, it generates many bubbles (Figure 3(a)), each 'singing' its own note, and from the overall sound we can determine the number and size of bubbles containing trapped atmospheric gas, which can form clouds[11,12] in the upper ocean (Figure 3(a)). These bubbles are responsible for the transfer between atmosphere and ocean of many hundreds of millions of tonnes of atmospheric carbon each year. However to quantify this climatically-important carbon transfer, it is not sufficient simply to know how many bubbles are injected into the ocean by breaking waves. One must also know how many are left some time after the wave has broken, after some bubbles have risen to the surface, and others have dissolved. To do this, we developed techniques to measure the 'silent' bubbles whose ringing ceased some time ago, based on projecting sound at the bubble and re-exciting them to emit sound. One particularly useful discovery[13] was that, when a signal with a high frequency (f_{i}) is projected at a bubble cloud at the same time as a signal at a lower frequency (f_{p}), then the bubbles that are resonant at f_{p} can uniquely scatter the frequency $f_{\mathrm{i}} \pm f_{\mathrm{p}} / 2$, allowing bubbles of this size to be identified from clouds of other bubbles[14-18]. By varying f_{p} , a cloud of bubbles could be scanned to count and size them all uniquely[19]. This was used to count bubbles in the sea, and as the basis for the development of a range of techniques suited to oceanic bubble counting[19-21], particularly in the surf zone where previous acoustical methods had lacked the ability to cope with the time dependent and nonlinear[21,22] effects that would occur there.

Using this range of signals we were able to equip a spar buoy[23,24] that was deployed from the Royal Research Ship *Discovery* in 2007 to measure bubble populations in the North Sea, data which we then use to model the transfer of gas between atmosphere and ocean. This was done to provide values for parameters that are key to understanding the carbon budget of the planet, and from there to approach the issue of climate change [Figure 3(b, c, d)]. This was part of the Natural Environment Research Council's UK Surface-Ocean/Lower Atmosphere Study (SOLAS), which has advised the House of Commons Science & Technology Committee[25] and informed a UNESCO report[26].



(a)



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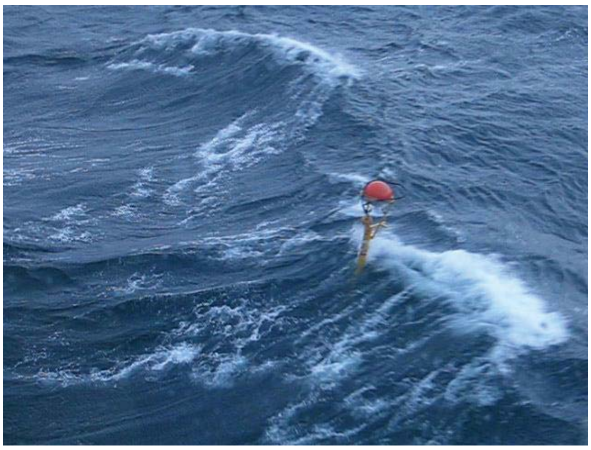
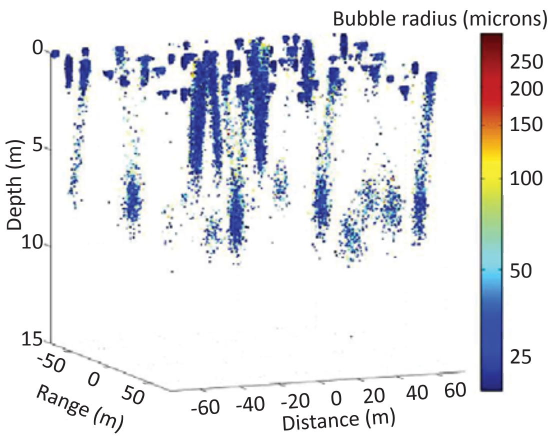


(c)



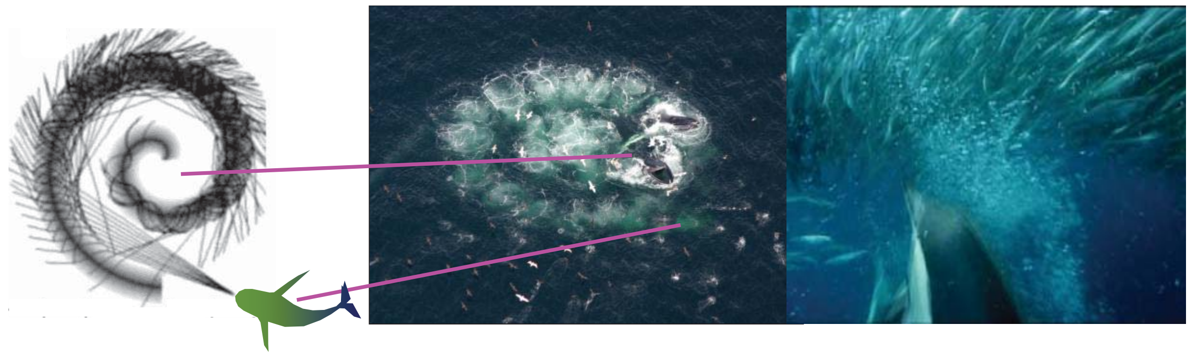
(d)

Figure 3. (a) Photograph of clouds of bubbles under waves at sea (photograph by the author). (b) Preparation to launch the spar buoy during cruise in 2007. (c) The spar buoy in the North Atlantic in 2007. (d) Plots of the distribution of bubbles trapped under breaking ocean waves in a region of ocean measuring 100 m by 120 m by 15 m deep. It was produced by combining the acoustic data from the cruise with models of ocean dynamics. The colour coding for bubble size shows that smaller bubbles (blue) can be drawn deeper by turbulence and ocean circulation than can the larger bubbles (red) for which the buoyant rise forces are stronger.

3 BUBBLES AND CETACEANS

I was struck by a photograph of whales forming bubble nets to trap fish. Although it had been known for decades[27] that whales blow bubbles to do this, the reason why the prey do not escape the trap was not known. I proposed an acoustical method by which the bubble net might operate[10,28-30]. Our modelling showed that the spiral bubble net traps the loud calls emitted by whales to produce an impassable ‘wall of sound’, whilst simultaneously creating a quiet zone in which the prey would congregate [Figure 4(a)]. When the net in the photograph was modelled, this ‘quiet zone’ occurred at the exact location where the rising whales feed [Figure 4(b)]. Although far from proven, this proposition has now entered the standard lexicon of whale watching tours and has featured on a number of TV shows. More details are available on the web[31].

Unlike humpback whales, dolphins use high frequency sonar to find prey, and the bubble nets they create [Figure 4(c)] would confound their sonar. Rather than accept that such dolphins would ‘blind’ their most spectacular sensory apparatus when hunting, I proposed that if the dolphins were to project specific sequences (even sequences as short as pairs) of sonar pulses at the bubbles, and add and subtract the echoes, they might make use of the nonlinear scattering by bubbles to distinguish the genuine target (the fish) from the clutter (the bubbles)[10]. Tests of this new sonar (TWIPS – Twin Inverted Pulse Sonar) in underwater test tanks, and at sea, indeed proved TWIPS could detect targets in bubble clouds[32,33].



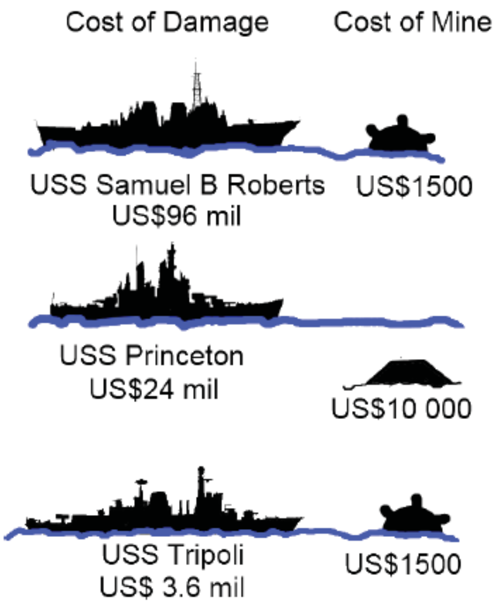
(a) (b) (c)

Figure 4. (a) Model (left) of acoustic rays from a photographed spiral bubble net (photograph shown in (b) is by Tim Voorheis / www.gulfofmaineproductions.com). The lines connect the proposed locations of the calling whale and the prey. (c) Image of a dolphin blowing bubbles to catch fish (Images courtesy of The Blue Planet. BBC).

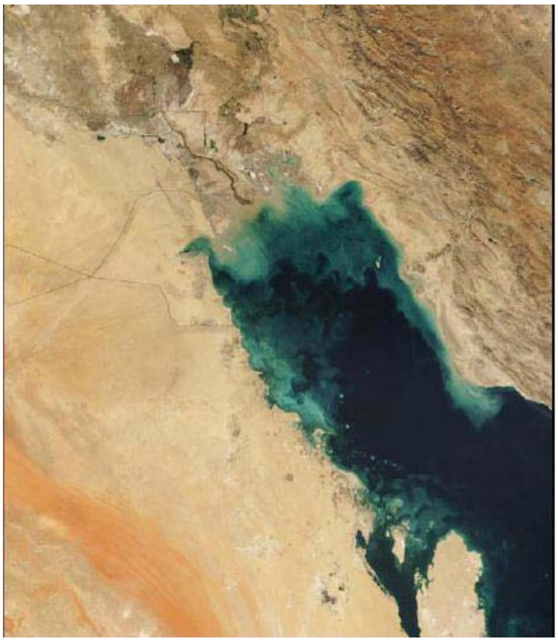
The importance of TWIPS to industry lies not in fishing, but in the detection of explosives. In recent years, sea mines purchased for only a thousand dollars each have caused millions of dollars of damage to shipping, and loss of life [Figure 5(a)]. This is because, like many coastal regions and river outflows, in the Persian Gulf bubbles and particles provide sufficient clutter to make mine detection extremely difficult [Figure 5(b)].

In such waters, manual searches by divers and military-trained dolphins have to date represented the only viable option for detecting targets. Rear Admiral W.E. Landay (Chief of Naval Research, Marine Corps for Science and Technology) is quoted[34] as saying:

‘The explosive ordnance disposal divers and the marine mammals run counter to the drive to get people out of the minefields, ... but they provide "so much flexible capability" that they are likely to remain. The divers and the mammals work mainly in very shallow water and the surf zone, which "continues to be the most challenging environment" for mine warfare’.



(a)



(b)

Figure 5. (a) Comparison of ship repair costs as a result of mine attack in recent years[35]. (b) Aerial image of Persian Gulf (image courtesy J. Descloitres, MODIS Land Rapid Response Team at NASA GSFC).

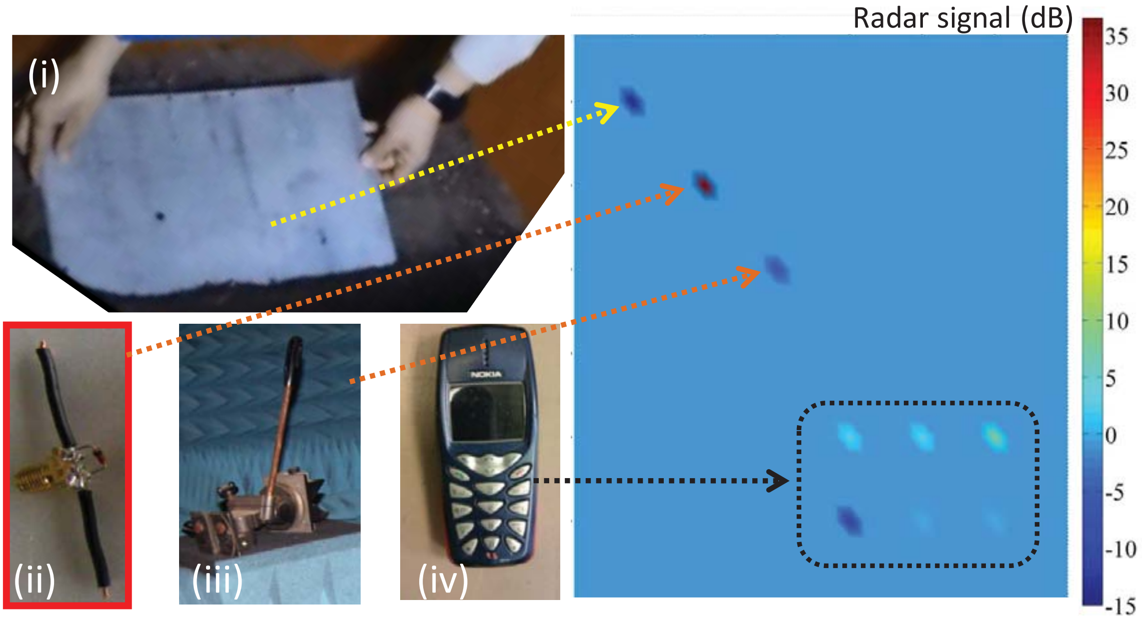
Therefore, sonar that could work effectively in bubble clouds would have significant implications for safety, cost and tactics, reducing the need for humans and marine mammals to go into minefields. Such a sonar would also enable rapid surveying of areas for mines to prevent delays to military, merchant, humanitarian and aid convoys, which could otherwise be delayed if there is even as much as the suspicion of mines being present.

Suspended particles [such as those seen in Figure 5(b)] prove challenging enough, and we provided the theory[36-39], validated by experiment, to "*allow improved prediction of the performance of high frequency sonar in the challenging environments of today's coastal warfare*" (S. Richards).

Bubbles proved to be a far more challenging factor for sonar than did particles[40], but TWIPS, and its successor[41,42] BiaPSS (Biased Pulse Summation Sonar), are today the only sonars capable of detecting such targets in bubbly water. More details on this topic are available on the web[43].

In addition to providing new sonars, and raising new questions about the sonar of dolphins[30,32,44], we recognized from the start that these new signals (TWIPS and BiaPSS) could work with radiations other than just sonar, such as MRI to improve the ability of scanning to distinguish healthy tissue from diseased[32,45]. One problem was the immediate need for a radar system that could distinguish genuine targets from clutter, the same problem the dolphin was facing in the bubble net. For example, service personnel searching for a roadside bomb must cope with the radar clutter produced by buried innocuous items, such as drinks cans and buried bicycle parts or construction materials. Therefore we developed a radar system that used a TWIPS-like technique to find a specific "target of interest" [Figure 6(a)(ii) – see the primary reference[46] for details] amongst the innocuous clutter [Figure 6(a)(i), (a)(iii) and (a)(iv)]. This TWIPR (Twin Inverted Pulse Radar) was so successful that scattering off the "target of interest" was more than 30 dB more powerful than the scattering off the false targets[46] [Figure 6(b)].

In addition to finding explosives, TWIPR can also help catastrophe victims. Re-tuning TWIPR to find mobile phones enables TWIPR to locate and identify people from the phone they carry when they are buried amongst clutter (for example in collapsed buildings, mudslides or avalanches) and can work even if the mobile phone is turned off, damaged, or its batteries have run down. More details on this topic are available on the web[47].



(a) (b)

Figure 6. (a) Various targets for TWIPR tests: (i) an aluminium plate, (ii) a specific "target of interest" [see the primary reference[46] for details]; (iii) a rusty bench clamp; (iv) mobile phones in various states. (b) Map of the TWIPR echoes detected in the experiment, with arrows linking the radar contacts with their sources in panel (a).

4 THE SEABED

Having developed a range of bubble detection techniques, we proposed[48] (Figure 7) using them to detect and quantify the emissions of gas from the seabed in three circumstances:

- Carbon Capture and Storage Facilities (our sensors were subsequently deployed on the world's first controlled gas release field trial);
- leaks from gas pipelines on the seabed (the system was subsequently deployed by oil and gas industries - representatives of the oil and gas industry stated that the technique "*is at least two orders of magnitude more sensitive than current model-based techniques for large, long pipelines*" (T.E. Bustnes 2011, personal communication; W. Postvoll 2011, personal communication);
- natural methane reserves in the seabed, and seeps from these.

The importance of natural methane reserves in the seabed is becoming increasingly clear. The implications of seabed methane go far beyond simply seeing it as a potential fossil fuel to exploit. Its release from the seabed into the atmosphere could have significant effects on climate. We developed systems for assessing its presence when in gas pockets in the seabed[49]. However in cold, deep waters, methane forms an ice-like hydrate with water: if it remains as hydrate, it is unlikely to be transported by nature from the seabed to the atmosphere. If it does reach the atmosphere, the ability to generate 'greenhouse' warming per molecule of methane gas is at least 20 times that of each CO_2 molecule[50]. The potential ability of climate change to warm ocean waters sufficient to release free methane gas bubbles from methane hydrate, which then rise into the atmosphere further to affect climate, is clearly is an issue of importance[51]. This is especially so because the global reserve of methane in the form of hydrate has been assessed[52] as being more than twice the worldwide amount of carbon to be found in all known conventional fossil fuels on Earth. We have therefore adapted the our acoustic bubble detection methods for monitoring methane release from the seabed. This, along with the CCS and pipeline applications, featured in the European Commission's environmental policy makers' news service[53]. More details on this topic are available on the web[54].

Other projects on seabed acoustics include:

- the development of acoustical methods[55] for the detection of the next generation of telecommunications optical fibres in the seabed, which will be more difficult to detect (when they need repair) than were previous generations (Figure 8);
- characterization of the seabed, for example to assist in civil engineering projects[56-59];
- calibration methods for acoustical instrumentation in the seabed[60]; and
- a seabed penetrating sonar[61,62], subsequently used by police, civil engineers etc., and now in commercial production (Figure 9).

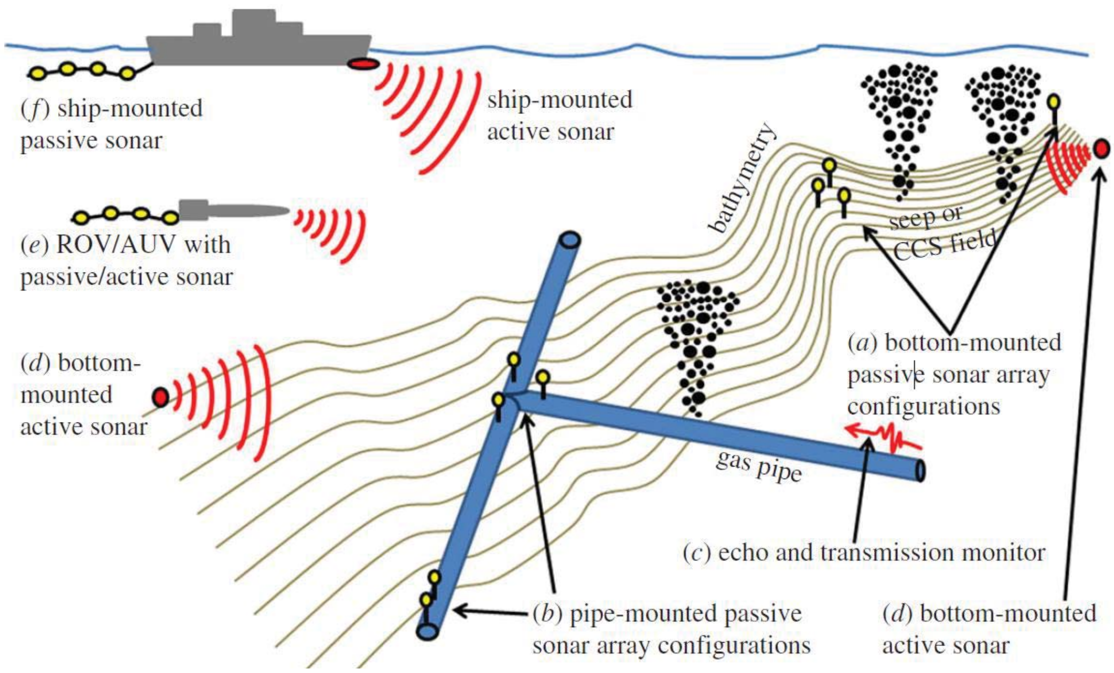
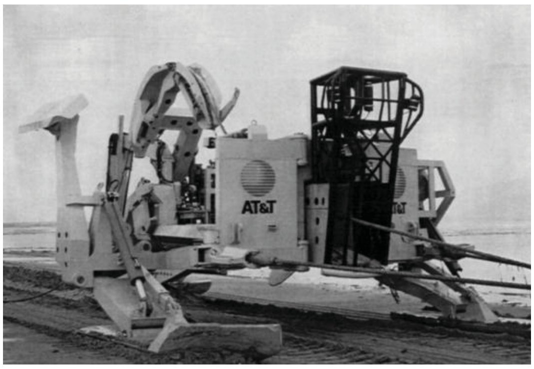
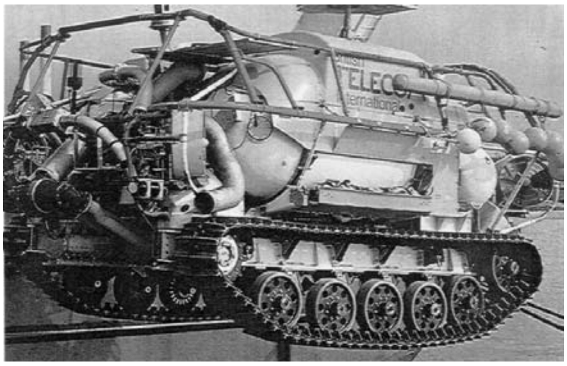


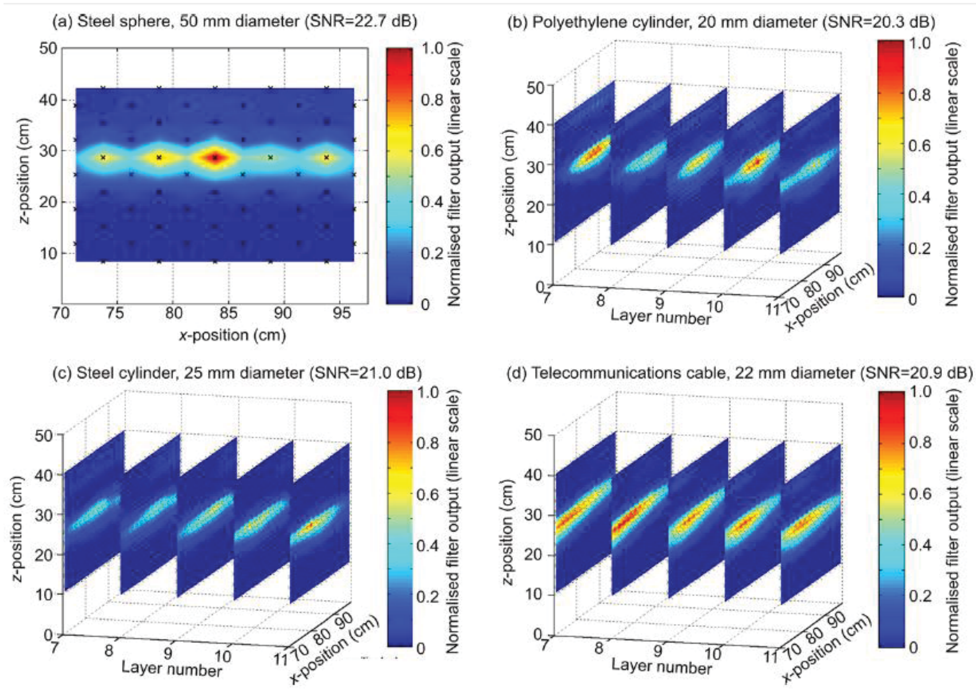
Figure 7. Proposal[48] for deployment of passive (yellow) and active (red) acoustic bubble detection systems of Sections 2 and 3 for monitoring for undersea gas leaks from gas pipelines on the seabed, and from methane reserves and from Carbon Capture and Storage Facilities.



(i)



(ii)



(iii)

Figure 8. (i) The 4 m long ‘Sea Plow VI’ towed underwater vehicle can bury cable to a depth of 1.1 m in the seabed at a maximum sea depth of 1 000 m. (From ROV Review 1993-94, WAVES magazine, Windate Enterprises Inc., 5th Edition.) (ii) The 3 m long ‘Seadog’ tracked underwater vehicle is used for cable burial, tracking and repair at a maximum sea depth of 275 m. (From ROV Review 1993-94, WAVES magazine, Windate Enterprises Inc., 5th Edition.). (iii) Results from the cable detection system developed by the author in a test tank[55]. The normalised, peak-squared, elastic-response-optimised, inverse filter output from a target region containing (a) a steel sphere of 50 mm diameter (SNR = 22.7 dB), (b) a polyethylene cylinder of 20 mm diameter (SNR = 20.3 dB), (c) a steel cylinder of 25 mm diameter (SNR = 21.0 dB) and (d) a real lightweight telecommunication cable of diameter 22 mm (SNR = 20.9 dB).

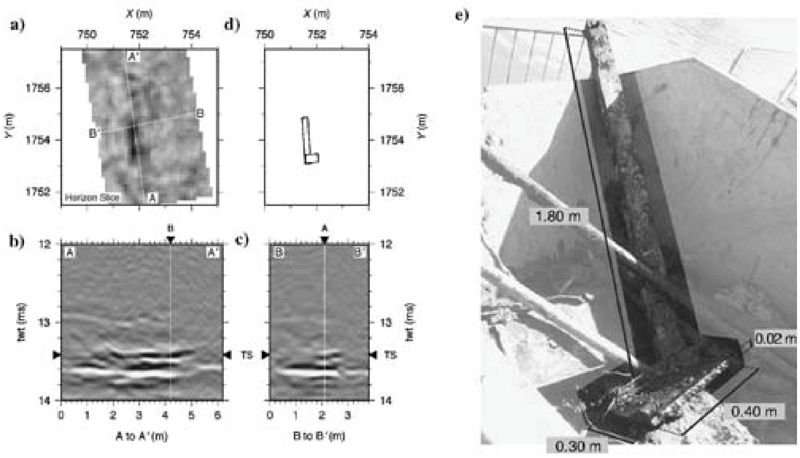
Kongsberg GeoAcoustics GeoChirp 3D sub-bottom profiler delivered to China

SUBSEA NEWS **5. May 2014**

GeoChirp 3D high resolution sub-bottom profiler provides three dimensional acoustical images of shallow sub-seabed structures and buried objects. It transfers the well-established principles of conventional 3D reflection seismics, used in hydrocarbon exploration, to high resolution chirp sub-bottom profiler technology.

The surface towed GeoChirp 3D incorporating a chirp sub-bottom profiler, 60 channel receive array together with GPS and MRU positioning solutions.

It has been used in a wide variety of applications, including marine archaeology, imaging buried wrecks of historical importance in the UK; marine geology, researching landslide mechanisms in Norwegian Fjords and locating buried objects in UXO (un-exploded ordnance) surveys. The First Institute of Oceanography (FIO), in Qingdao is its first commercial customer. China's internationally reputed research institution is looking forward to applying the state of the art technology in its line of research. The system has been originally developed at the National Oceanography Centre, Southampton, UK with support from Kongsberg GeoAcoustics, who now have made this unique technology available in the commercial market.



A buried object consisting of a small metal plate attached to a wooden pole as imaged by the 3D high resolution sub-bottom profiler. The 3D data volume is represented by two vertical and one horizontal slice through the sub-seafloor, revealing the geometry of the buried object in great detail.

Figure 9. Recent press release from Kongsberg on first sale of GeoChirp 3D sonar to China.

5 BUBBLES IN PIPELINES

A very significant challenge was the commission to measure the population of helium bubbles in 20 tonnes of liquid mercury in the $1.4 billion Spallation Neutron Source (SNS) Target Test Facility (TTF) at Oak Ridge National Laboratory (ORNL), Tennessee (the most powerful pulsed neutron source in the world). In ORNL's SNS, this mercury is pumped through a stainless steel target vessel, heat exchanger and pipework system. When it enters the target vessel, the mercury generates neutrons when it is impacted by a proton beam, generated (after several stages) by a linear accelerator (Figure 10). The hard radiation was expected to embrittle the steel of the target vessel walls, requiring scheduled replacement. However late in the facility construction it was recognized that beam-pulse induced cavitation damage could make unscheduled target replacements necessary, costs for which could be as great[63] as $12M each time depending on rescheduling. Both targets 1 and 2 were replaced during planned maintenance periods without interruption to the user program. However, in April 2011 unanimous indications from leak detectors in target 3 occurred in the midst of neutron operations (outer shrouds contained any leak, as per design). ORNL had already put in place a number of R&D programs. From these a leading candidate solution was the proposal to introduce non-condensable helium gas bubbles into the mercury in SNS, either to form a gas wall to protect the steel where the beam enters the target[64,65], or to provide a population of small bubbles in the bulk of the mercury to absorb the pressure pulse and reduce vapour cavitation formation (and the erosion it generates) on the wall.

Figure 10. Schematic of the Spallation Neutron Source at Oak Ridge National Laboratory, Tennessee. The hydrogen ions for the linear accelerator are generated in the 'front end' building at the top left of the picture, and are accelerated down the linear accelerator (shown in red) to the ring, where protons are accumulated. During repeated circulation of the ring, more protons are added to 'paint out' the complete 200 mm x 70 mm elliptic proton beam. When this is complete (which occurs 60 times per second), the proton pulse is released into the 'target' building, the centre of which houses the sarcophagus in which the actual mercury target is housed. A possible future target building is shown in ghost outline (image courtesy of ORNL).

We were commissioned to generate detectors to check what population of bubbles had been added. The task was significant, since the bubble detection methods outlined in Sections 2 and 3 assumed the bubbles existed in infinite volumes of liquid, and using these would give erroneous results for SNS[66-70]. Therefore after characterizing the bubble-free acoustics of the pipelines[71,72], a solution was developed[63]. However high-level ORNL budget cuts half way through the contract required a completely different approach, which we also developed[73,74] (based on successful technology we invented for the pottery industry[75]), and fitted to SNS TTF (Figure 11). The technology was also adapted for outreach[76,77]. More details on this topic are available on the web[78].

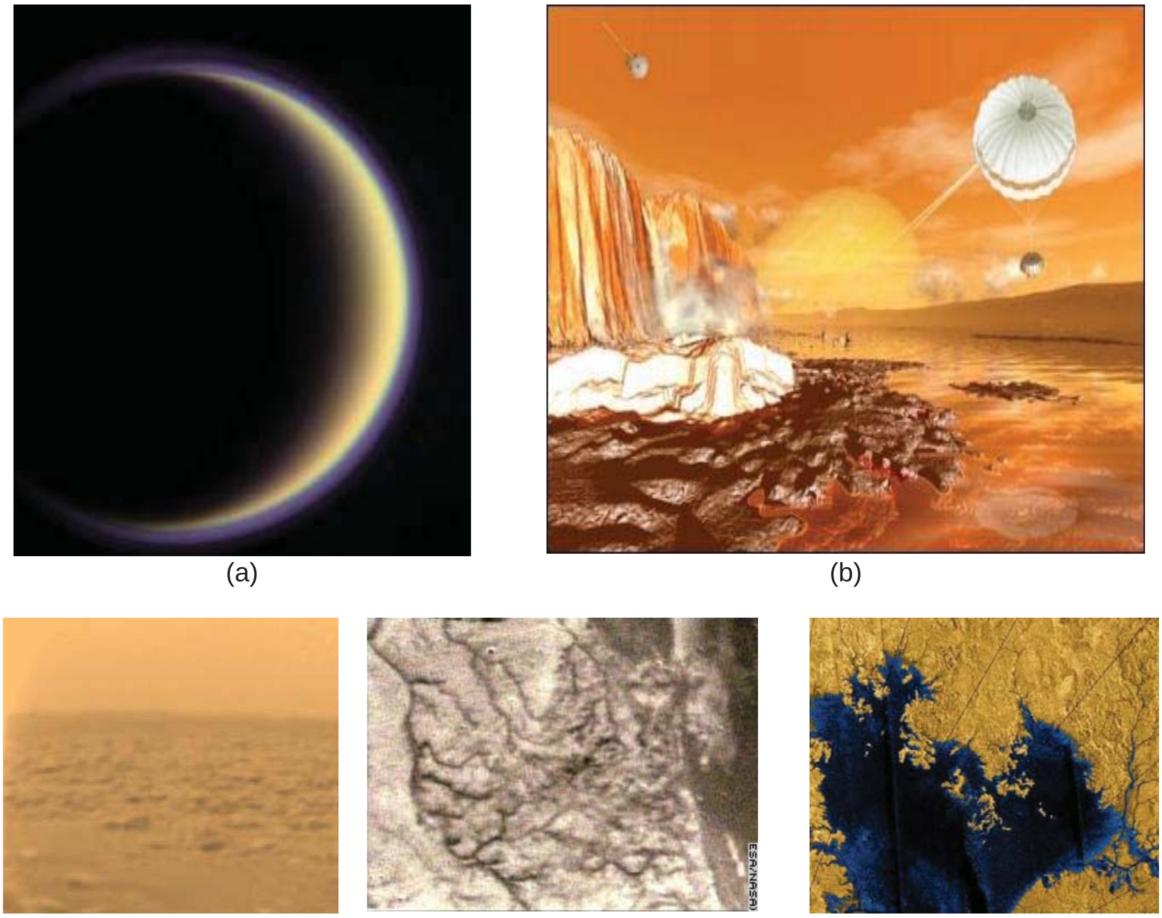
Other pipeline work includes designing ultrasonic devices for pipelines for the food, pharmaceutical and domestic product industries, to enable them to manufacture products with greater safety and reduced cost.

Figure 11. The author and a member of ORNL staff (Mark Wendel) fitting the bubble detectors to the mercury-filled steel pipelines of SNS TTF.

6 EXTRATERRESTRIAL ACOUSTICS

The ability to infer the bubble sizes generated from the sounds of waterfalls, breaking waves, and rainfall (as discussed in Section 2) was used to create[10,79] the possible sound of 'methane-falls' (waterfalls made up of liquid methane and ethane) on Saturn's largest moon, Titan. As the Cassini-Huygens mission approached Titan in 2004, no-one knew what the surface would be like because Titan is shrouded in a thick fog [Figure 12(a)]. However one body of opinion held that, with a 93 K

surface temperature, the cold conditions and dense atmosphere would allow for the existence of lakes and possibly methanefalls on Titan [Figure 12(b)].
Prior to Huygens' landing, we simulated the sound that would be made were Huygens to splashdown in a lake, and the sound that a probe on the surface of Titan might detect if it landed with its camera facing away from the methanefall. Huygens was very successful, and although its images from its landing site revealed a barren landscape [Figure 12(c)], during descent some indication of topography that might have been carved by flowing surface liquid was revealed [Figure 12(d)], and later radar observations by Cassini revealed lakes [Figure 12(e)].



(a) (b)

(c) (d) (e)

Figure 12. (a) Image of Titan. (b) Artist's impression of the *Huygens* probe parachuting through Titan's atmosphere, having previously detached from the *Cassini* vehicle (seen in the upper left of the image). (Painting by D. Seal). (c) The surface of Titan as imaged by the Huygens probe after landing. (d) Images of the surface of Titan taken by Huygens during descent. (e) False-color Cassini radar image of Titan's surface. Blue coloring indicates low radar reflectivity, attributed to hydrocarbon seas, lakes and tributary networks filled with liquid ethane, methane and dissolved nitrogen. All image credits: NASA/JPL/Caltech).

The objective of our research was to provide material for outreach, but also to explore the extent to which we might start to construct the soundscapes of other worlds,. Given that despite all the planetary probes sent out, we have never yet heard the soundscape of another world[80], this work was conducted for the purpose of:

- enabling better design of microphones and sound sources for use on future planetary probes (for example, accounting properly for the effect of structures associated with the microphones[72,81]);
- improving the design of missions exploiting acoustics in planetary exploration (by, for example, correcting the analysis used to predict the correct placement of detectors on ice-covered moons like Jupiter's moon Europa, with the purpose of using sound to explore the vast water oceans beneath the ice[82-84]);
- exploring the extent to which we might interpret sounds picked up by planetary probes to ascertain key features about the world the probe is exploring.

For this latter objective, in designing the algorithms to simulate the sounds of worlds, we were able to provide a device, licensed to planetaria, which not only allows the audience to hear the simulated sound of the world under discussion, but in live presentations allows the presenter to use the voice they would have on a given planet (if they could speak and live), when telling schoolchildren about that planet[85,86]. More details on this topic are available on the web[87].

7 BIOMEDICAL BUBBLES

Given the ability of bubbles driven by ultrasound to cause physical, chemical and biological effects, and the increasing power outputs of ultrasonic foetal scanning devices in the 1980s, we began research into the potential for, and conditions under which, ultrasound could change tissue[88-91]. Sometimes such changes could be beneficial (for example in dentistry[92] or tumour therapy[93] - Figure 13), whilst at other times they should be avoided (for example during ultrasonic foetal scanning). This included the world's first assessment from living human tissue of ultrasonically-induced luminescence (indicative of high energy cavitation)[94]. Given that most of the models associated with the behaviors of bubbles under ultrasound harked back to parameters derived only for steady state conditions, yet many of the clinical applications used ultrasonic pulses, we paid particular attention to the effect such pulsing had on the bubble activity and its potential to cause chemical and biological changes[89,90,95,96].

(a) (b)

Figure 13. (a) The author and colleague from the Institute of Cancer Research at the John Radcliffe Hospital, Oxford. (b) The lighter-coloured region of tissue has been heated by focused ultrasound to the extent that would make it non-viable *in vivo*.

(a)

(b)

Figure 14. Examples of (a) traditional and (b) more recent ultrasonic scanning results.

These research investigations had a number of outputs:

Guidelines: in the past 30 years the quality of ultrasonic image for fetuses has increases dramatically (Figure 14), in large part because the devices have exploited higher frequencies, giving better spatial resolution. However higher frequencies are more strongly absorbed, and so to achieve good signal-to-noise ratios on reception, the output power has tended to increase[97,98.99]. To provide a proper safety framework for the conduct of ultrasonic scanning, the World Federation for Ultrasound in Medicine and Biology produced guidelines for foetal ultrasound scanning[100]. Since those guidelines were published, around 2 billion births have taken place.

DosePro™ is the only commercially available prefilled disposable needle-free drug delivery system for subcutaneous injection. Regarding its development, Toby King (CEO of Bowman Power Group) said:

> "*Fundamental published work on conical bubbles by Leighton et al.*[101-103] *informed Weston Medical in the development of a needle-free injector (for subcutaneous drug delivery). In 2002 the business was worth £6 million, but development was stalled by performance issues. Weston Medical contracted Leighton to address performance. His solution enabled further development, such that in 2006 the company Zogenix was formed around this technology, and has now raised a total of over $150 million of Venture capital and loans, primarily to fund approval (successfully achieved in the USA in last year) and marketing of the product with a migraine drug, now called Sumavel Dosepro. The current global market for just this one drug (Sumatriptan) is over $1 billion per year. The needle-free injector is now selling well in the US and the EU- they have just made their millionth device, and quarterly revenues have grown from nothing to $7 million in only a year*".

LithoCheck™ is a device (originally called the Smart Stethoscope[104,105]) that was invented to monitor the ultrasonic kidney stone therapy known as Shock Wave Lithotripsy[106,107] (SWL) (Figure 15). Why was the device needed? SWL focuses a preset number of shock waves (~3000) onto kidney stones to break them into small pieces, which can then be dissolved by drugs or passed from the body in urine. However, it is difficult for the clinician to assess during treatment when (or even if) the SWL has succeeded in breaking the stone: SWL suites come with a range of sensors, but even with these an experienced clinician can have difficulty assessing whether a stone has been broken at the end of the treatment. Currently 30-50% of patients are sent home with the stone intact, and must return for retreatment: this ties up theatre and clinician time, adds to waiting lists, and prolongs patient pain and journeying to hospital. Conversely, in an unknown proportion of cases, the stone fragments before the full 3000 shocks are delivered, and having a device that would allow the clinician to stop the treatment at this point would avoid exposure of the kidney to more shocks than necessary (such exposure can damage healthy kidney tissue, leading to pain, haemorrhages, thrombi, arrhythmias, hypertension, reduction of renal functionality and infections)[111]. LithoCheck™, proved to be sufficiently effective to win the Medical and Healthcare Award at the 2008 Engineer Technology and Innovation Awards. On the topic of LithoCheck™, Dr Fiammetta Fedele of Guy's and St Thomas' NHS Foundation Trust [GSTT] said**:**

> **"***Prof. Leighton's predictions*[108-111] *of the acoustic signals emitted when bubbles collapse against kidney stones during shock wave lithotripsy (SWL) led (through collaboration [of Southampton University] with GSTT and Precision Acoustics Ltd.) to a £5,000 passive acoustic sensor (patent applied for). When placed on the patient's skin this sensor diagnoses successful SWL treatments (with 94.7% accuracy in clinical trials, compared to the 36.8% achieved by clinicians with the current ~£1M state of the art equipment suite)*[112,113]*. An accurate diagnostic is needed to conform with the 2004 'THE NHS IMPROVEMENT PLAN: PUTTING PEOPLE AT THE HEART OF PUBLIC SERVICES'*[114] *of reducing the 'patient pathway', because currently 30-50% of SWL patients require re-treatment and an unknown number are overdosed. The NHS is trialling it as part of major plans to reduce inaccurate diagnoses and ineffective treatments*[111]*. GSTT has used the sensor on over 100 patients***".**

The 'patient pathway' mentioned above is the NHS route from diagnosis to final treatment, and the aim of reducing this pathway includes reducing the occurrence of misdiagnosis, re-treatments, inefficient treatments, and the introduction of effective screening processes. Reducing the 'patient pathway' was a major aspiration in the NHS Improvement Plan[114]. LithoCheck™ can do this for standard lithotripsy treatments[112], firstly by reducing underexposures, and so decreasing retreatment rates, and so lessening the burden on theatres and the associated staffing and booking resources[112]. Secondly it also reduces overexposures (which can lead to the side-effects listed above) by reporting in real time in theatre when the stone has fragmented, allowing treatment to be stopped before the intended 3000 shocks have been delivered. Thirdly it can screen for those kidney stones that will never respond to SWL, because the clinician can use LithoCheck™ to monitor the first 100 shocks (fewer than would cause the side effects listed above) out of the ~3000 that the clinician intends to send into the patient: if the LithoCheck™ report on the first 100 shocks indicates that the stone in question will be unresponsive to SWL, the clinician can cessate SWL treatment and send the patient for some alternative stone removal procedure[111].

Osteoporosis causes 60,000 hip fractures each year in Britain. We published the proposition and the first theoretical framework[115] by which ultrasonic scans of bones from different directions can be compared to assess bone health and its deterioration. Figure 16 shows the 'honeycomb'-like structure of cancellous bone within the thicker outer shell of cortical bone. The fact that cancellous bone tends to develop its bony rods (trabeculae) with preferred directions ('anisotropy') reflects the need for that bone to cope with pressures and stresses peculiar to its location. The premise of the research was that, as bone health deteriorates, this anisotropy becomes less pronounced, which can be measured by monitoring ultrasonic propagation in two different directions. Figure 17 shows the first measurement[115] (with comparison to the first predictions) of anisotropy in cancellous bone. The theory[115] (solid lines) predicted that if phase velocity is measured as a function of the angle of refraction through the bone, there will be two waves detected, and their speeds would vary with angle. Ultrasonic phase velocities where the trabeculae are aligned with the ultrasound beam (90^o on the abscissa) differ very much from those when the two are perpendicular (0^o on the abscissa). The proposition[115--119] was that as the structure in cancellous bone deteriorates, this difference is gradually lost.

(a) (b)

Figure 15. (a) An early prototype being tested in clinic by the author (on the right), Dr Fedele (middle) and a radiographer (the image of the patient has been replaced by white pixels). (b) The Lithocheck™.

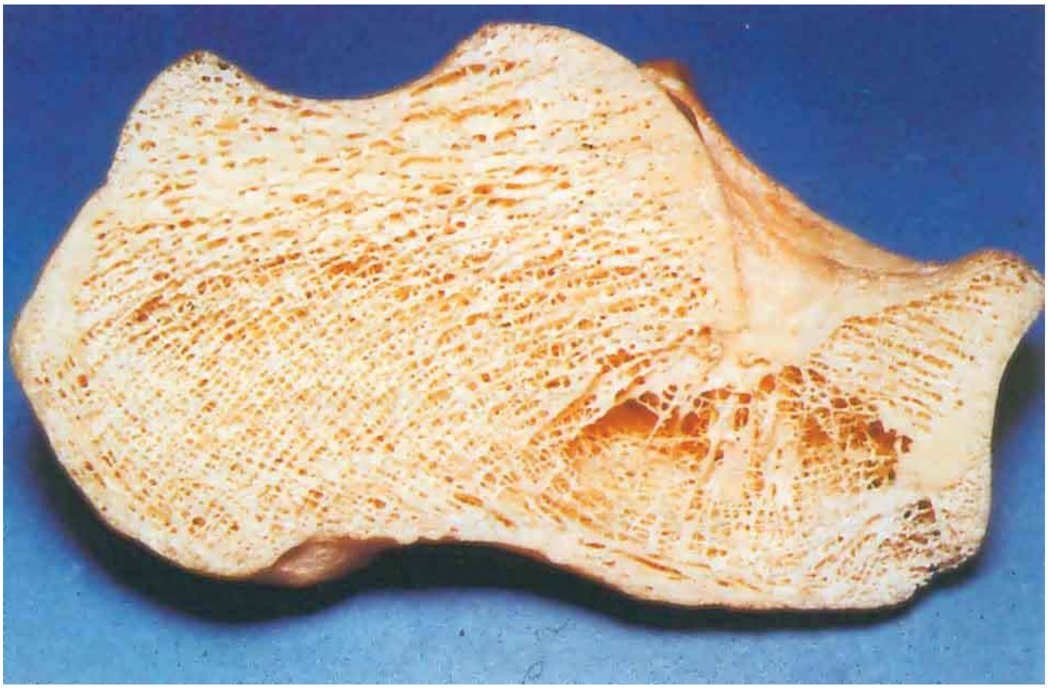


Figure 16. The ‘honeycomb’-like structure of cancellous bone can be seen within the thicker outer shell of cortical bone.

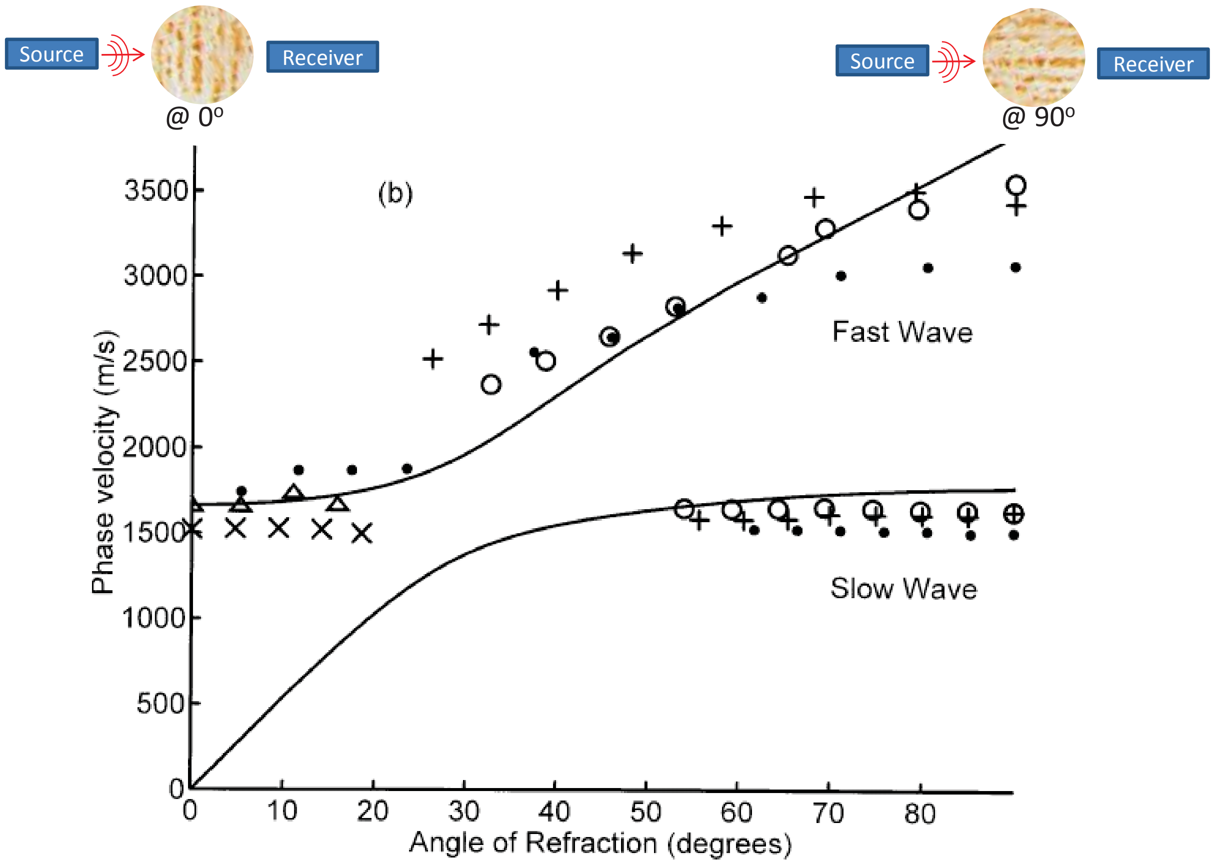


Figure 17. The first measurement[115] (compared with the theoretical predictions) of anisotropy in cancellous bone. Data (here at 920 kHz) here shows measurements from six samples of bovine bone (symbols $+, \bigcirc, \bullet, \times, \Delta$). Note that one $\bullet$ sample generated the data above 30°, and another sample (also labelled $\bullet$) generated the data below 30°.

8 COLD WATER CLEANING

The preceding section introduced how, during biomedical therapy, we might wish to promote and control the ability of ultrasonically excited bubbles to cause physical, chemical, or biological changes to their surroundings. Alternatively, during diagnosis, we might wish to suppress or avoid such ultrasonically-induced changes.

Outside of the biomedical arena, we studied the ability of bubbles activated by sound (and other pressure fluctuations) to cause changed in liquids and nearby solids, with application to:

- the erosion of hydroelectric turbines[120];
- the optimization of ultrasonically-induced chemical reactions[121-126];
- the construction of erosion sensors[127-134].

Of particular interest was the growth of surface waves[135-138] on the bubble wall (Figure 18), which if controlled could greatly enhance the rates of chemical reactions[139-142] and electrodeposition[143]. However, the most important application we proposed was in the ability of such waves to generate ‘cold water cleaning’.

Traditional ultrasonic cleaning baths are limited in that they cannot clean objects that are too large to fit in the bath, and cannot be taken to objects with complex geometries in order to ′clean in place′. Furthermore the object to be cleaned sits in a ′soup′ of contaminated liquid, and whilst cavitation fields can be set up under test conditions, immersion of the object to be cleaned can significantly degrade the bath′s performance by disrupting the sound field. An alternative technique, which does not use ultrasound is the commercial pressure-/power-washer, where high speed jets of water and cleaning agent are pumped onto a surface. Although these can ′clean in place′, they pump large volumes of water, and produce significant volumes of contaminated run-off and contaminated aerosol, both of which are hazards for secondary contamination of users and water supplies. The momentum of the water and pump requirements mean they are difficult to scale up. The challenge here was to produce a low volume flow technique for ultrasonic cleaning in place, benefits being that it operates with low flow rates (1-2 litres per minute), and there is no need to expend energy on heating the water.

The proposition that cleaning could be achieved using low volumes of cold water, without additives, in a gentle flow, was an ambition for many years[104,144]. The challenges for cleaning are not simply related to today’s use of too much water, too many additives, and too much energy to heat the water[145]. An additional challenge is that, whilst it can be simple to clean flat surfaces, it can be more difficult to remove dirt from crevices, cracks and pores.

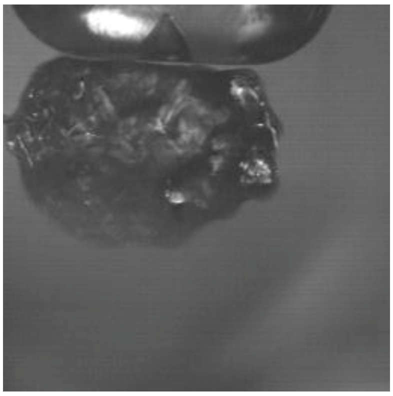


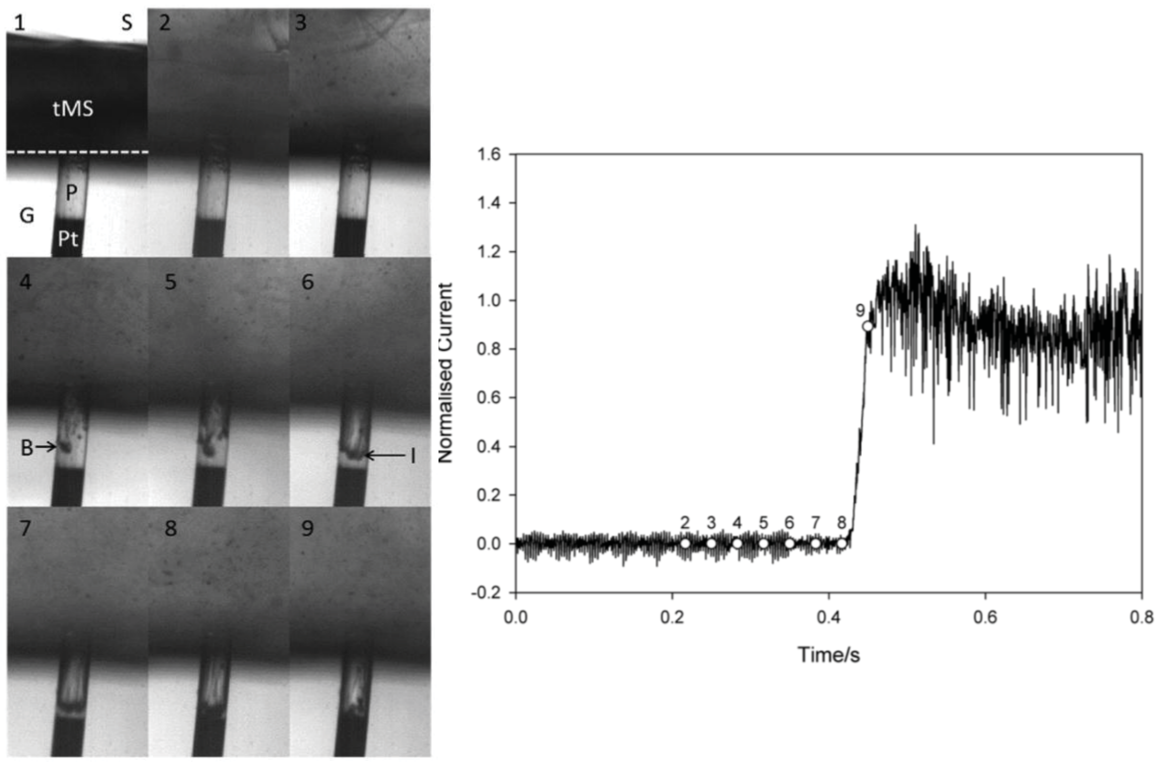
Figure 18. Surface waves on a bubble wall.

The solution was to use ultrasound to generate surface waves that cause the bubbles to act like tiny ‘scrubbing machines’, and furthermore to make the bubbles seek out crevices and cracks and clean within them. Figure 20(a) shows a sequence of selected frames demonstrating the effect of ultrasonic cleaning in a glass block that contains a small cylindrical pore[146]. The surface of the glass block and the pore are initially covered with a contaminant (tMS), which appears dark in the top half of frame (1) (its thickness within the small pore is not enough to make the image there opaque). At the base of the pore is an electrode, the current from which indicates whether the pore is clean or contaminated. At the start of insonification, the current is zero [frame (1), at time zero]. By 0.2 s [frame (2)] there has been substantial removal of the contaminant from the surface of the glass block, but the electrode current shows that the base of the pore is still dirty. By frame 4, however, the bubbles (one is labelled ‘B’) can be seen entering the pore, and the walls of the bubbles are rippled by surface waves that create shear in their vicinity, removing contaminant. The bubbles are driven by the acoustic forces towards the base of the pore, and by frame 6 only a small layer of contaminant remains in the pore (its upper surface labelled ‘I’). When the bubbles reach the base of the pore [frame (9)] there is a rapid increase in the cleanliness of the electrode.

How do the acoustic forces cause the bubbles automatically to find the pore? When subjected to an external sound field, bubbles scatter that field, and that scattered field can influence the dynamics of nearby bubbles. When the bubble is near a flat solid surface (wall), the field it scatters is reflected off the wall, and returns to drive the bubble that caused it. From the bubble's point of view, the wall is acting like an acoustical mirror, and effectively the bubble acts as if there were a mirror image of itself on the other side of the wall, and equidistant from it. Two bubbles doing the same thing in a sound field attract[147], and so the bubble is attracted to the wall, and stays on it rather than being flushed away. The bubble then wanders over the wall, cleaning as it goes, but if it sees a crevice, it effectively sees the multiple images that are produced when many mirrors are angled to one another. Therefore the bubble is attracted into the pore, and cleans it.

The StarStream™ device consists of an acoustic horn in which ultrasound and bubbles are generated. These travel in the water that flows through the horn, onto the surface to be cleaned. A prototype was demonstrated on a German TV show[148] (Figure 20)

StarStream™ technology won the 2011 Royal Society Brian Mercer Award for Innovation. It also won the 2012 Institute of Chemical Engineering Award for "Water Management and Supply". John Melville, MD of Ultrawave Ltd. described StarStream™ as "*the only true technological leap forward in ultrasonic cleaning that we have seen for decades*". In 2014 Ultrawave will market the commercial units (Figure 21).



(a) (b)

Figure 19. (a) A sequence of selected frames (filmed at 3000 frames per second, exposure time of each frame was 1/44 000 s) showing the effect of ultrasonic cleaning in a glass block (whose upper surface is indicated by the dashed white line) that contains a cylindrical pore (125 mm diameter, ~350 mm depth, labelled 'P'). The glass (labelled 'G') is in a solution of 5 mM $K_3Fe(CN)_6$ and 0.1 M $Sr(NO_3)_2$ (labelled 'S') in an emulsion of water and F54 surfactant. The contaminant is labelled tMS. For details see the primary source[146]. (b) Plot showing the normalised current recorded at a platinum electrode at the base of the pore as a function of time [the electrode is labelled 'Pt' in panel (a)]. The numbers above the time history correspond to the frame numbers in panel (a). The current has been normalised to the average current recorded by the electrode in a clean pore under the same insonification conditions.

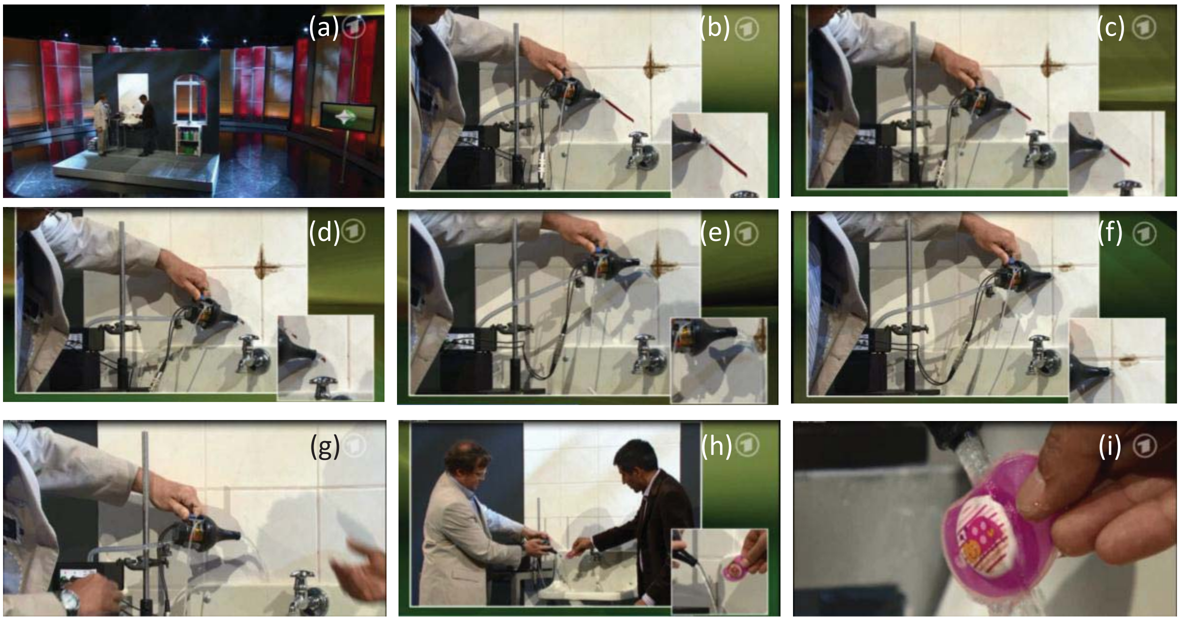


Figure 20. Frames from a TV show[148] where (a) the author is invited to a mocked-up kitchen on stage, and (b) is presented with lipstick and mud to clean from kitchen tiles. Using just cold water with no additives, and a water flow of between 1 and 2 litres per minute, the StarStream prototype quickly removes the lipstick (frames (c),(d)) and mud (frames (e),(f)) to leave a clean kitchen (frame (g)). The presenter the produces (h) a dirt-covered baby pacifier, which StarStream (i) quickly cleans.

Figure 21. The third generation version of StarStream™ that Ultrawave Ltd. is commercially producing in 2014.

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