

The acoustic bubble: Ocean, cetacean and extraterrestrial acoustics, and cold water cleaning

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2017 J. Phys.: Conf. Ser. 797 012001

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The acoustic bubble: Ocean, cetacean and extraterrestrial acoustics, and cold water cleaning

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Abstract. This paper summarizes the content of a plenary lecture on the author's personal research into the interactions between bubbles and sound fields, covering particular topics involving the climatically important gas exchange between atmosphere and ocean, the implications of bubbly ocean water to marine mammals that use sound, and the opportunities afforded by incorporating acoustical sensors onto probes launched to investigate other worlds in our solar system. It closes with recent data on the opportunities of bubble acoustics to investigate methods of cold water cleaning.

1. Introduction

Gas bubbles in liquids have an extraordinary ability to interact with sound fields. Although traditionally many people date the start of studies on collapse cavitation to the 1917 work of Rayleigh [1], in fact Rayleigh's well known analysis was predated by some 70 years by Stokes' handwritten solution to an examination question on the problem that he set in 1847 for less able physics undergraduates (see Ref. [2] for details). Those analyses were dominated by the effect of the inertia of the intruding liquid as it collapsed towards the centre of the void. Noltingk and Neppias [3,4] examined how such a cavity could be created and so introduced some permanent gas into the void, although the dynamics of the collapse were still dominated by the liquid inertia. The introduction of permanent gas harmonized the description of such 'inertial' cavitation with the famous 1933 description of non-inertial cavitation by Minnaert [5], where the effects of liquid inertia and gas stiffness are balanced to determine the natural frequency of oscillation of a pulsating bubble.

As Minnaert himself hypothesized, bubbles generate the song of a babbling brook [5,6], and ocean sounds through breaking waves. Such ocean sounds, and the way the oceans scatter and absorb sound, have since helped us understand the global carbon budget, as this paper will outline, Section 3 will describe how the particularly dense clouds of bubbles are produced in the ocean by humpback whales to form 'bubble nets' to catch prey, and speculate on the acoustical implications for this. The acoustical implications are wholly different when dolphins hunt with bubble nets, as they must adapt their sonar to avoid the bubbles themselves preventing them from finding their prey using echolocation.

Section 4 will explain how a desire to predict the sounds of Titan prior to the first probe landing there, led to a wider exploration of the numerous ways that we might use and observe sound on other worlds. Particular attention has been paid to improving the understanding of extraterrestrial acoustics so that our familiarity with sound on Earth does not lead us into assumptions that introduce errors into the design of acoustic sensors for probes, or produce erroneous interpretations when we eventually collect acoustic signals from other worlds.



To conclude the paper, Section 5 describes a new application of bubble acoustics, namely cold water cleaning without additives, and discusses its possible application in a range of scenarios where the use of cold water is preferable or unavoidable.

2. Bubble detection in the natural world

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)].

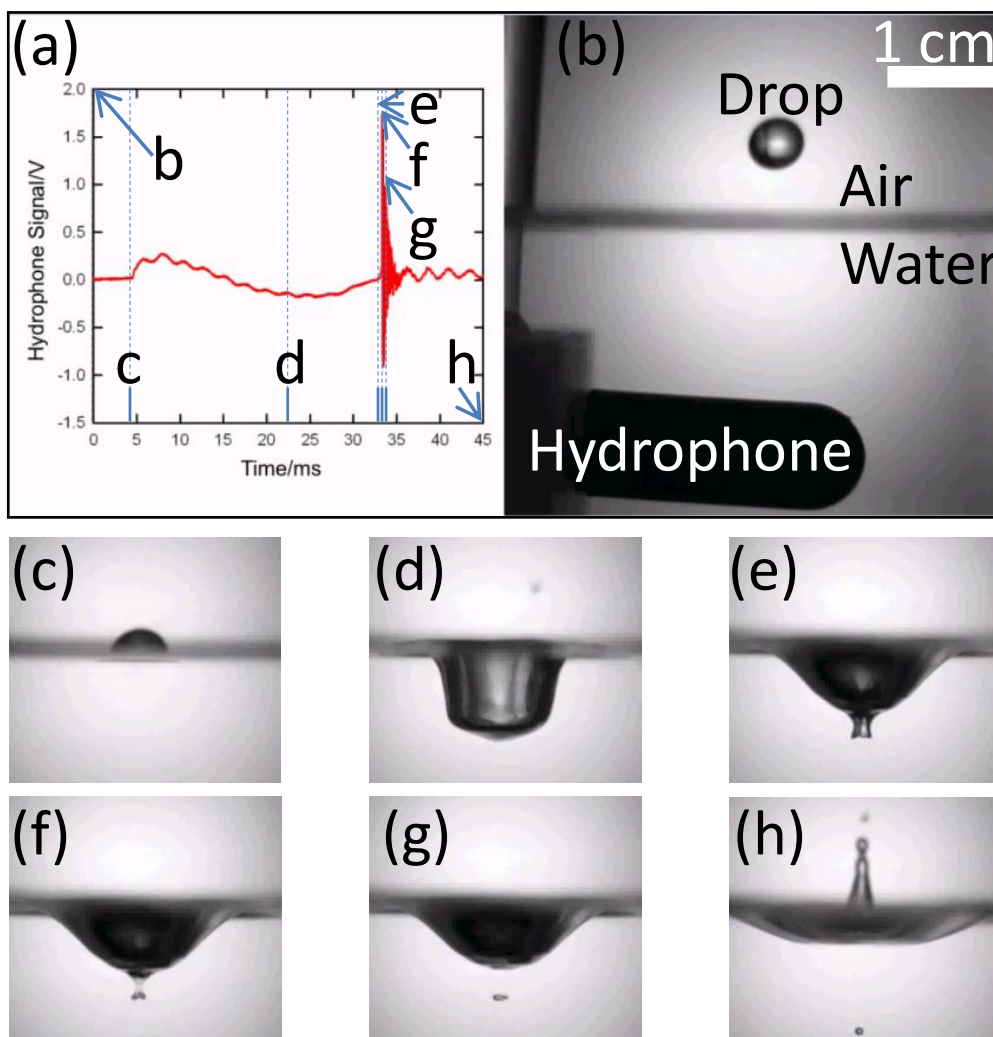


Figure 1. Synchronized hydrophone record and video frames (selected from a film recorded at 10,000 frames per second) for the sound produced by the impact of a droplet on a water-air interface. (a) The hydrophone output (in red, with the timing of subsequent frames labelled (b)-(h) showing the impact 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)).

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 [5]. Therefore from the pitch of the ‘plink’, one can determine the size of the bubble. The first count of the size distribution of bubbles [6] entrained in the natural world, made using the sounds they generated, was undertaken in the early 1980s. This led to similar counts for the bubbles trapped by rainfall over the ocean [7,8], and today we see the deployment of at-sea acoustic monitors for rainfall [9]. The technique was also deployed in the ocean [2,10,11] to detect bubbles trapped under breaking sea waves. When an ocean wave breaks, it generates many bubbles, 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 [12,13] in the upper ocean. 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 [14] 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 $f_i \pm f_p / 2$, allowing bubbles of this size to be identified from clouds of other bubbles [15-19]. By varying f_p , a cloud of bubbles could be scanned to count and size them all uniquely [20]. 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 [20-22], particularly in the surf zone where previous acoustical methods had lacked the ability to cope with the time dependent and nonlinear [22,23] effects that would occur there.

3. Cetacean acoustics

Our ability to model the scattering of sound by undersea bubbles allowed us to postulate the mechanism by which humpback whales trap prey within spiral bubble nets. Although it had been known for decades that whales blow bubbles to do this, the reason why the prey do not escape the trap was not known [2]. Our models (Figure 2(a,b)) 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, this zone occurring in the model at the location where the rising whales feed (as photographed in Figure 2(c)) [24].

However, unlike humpback whales, dolphins use high frequency sonar to find prey, and the bubble nets they create (Figure 2(d)) would confound their sonar. Rather than accept that dolphins would ‘blind’ their most spectacular sensory apparatus when hunting, we set about proving that a previously unknown type of sonar processing (TWIPS) could detect prey in bubble nets [25, 26], and showed this to work with dolphin sonar calls [27]. Although the question of whether odontocetes use such a method or not is still open to question [28, 29]. Industry is now developing this to protect shipping in coastal regions such as the Persian Gulf, where clouds of bubbles and particles in the near-shore waters make mine detection difficult (Figure 3(a)). Realizing that this new processing system could work with radiations other than just sonar, we used it to develop a radar system (TWIPR) where the scattering off circuitry from a bomb trigger was in excess of 30 dB more powerful than the scattering off other targets (Figure 3(b)) [30]. With the ability to detect mobile phones as readily and selectively as bomb triggers, TWIPR can help to find buried targets of interest (bombs, people carrying phones buried by collapsed buildings or avalanches) where normal radar would not be able to identify the genuine target from other debris (typified in Fig 3(b) by (i) & (iii)).

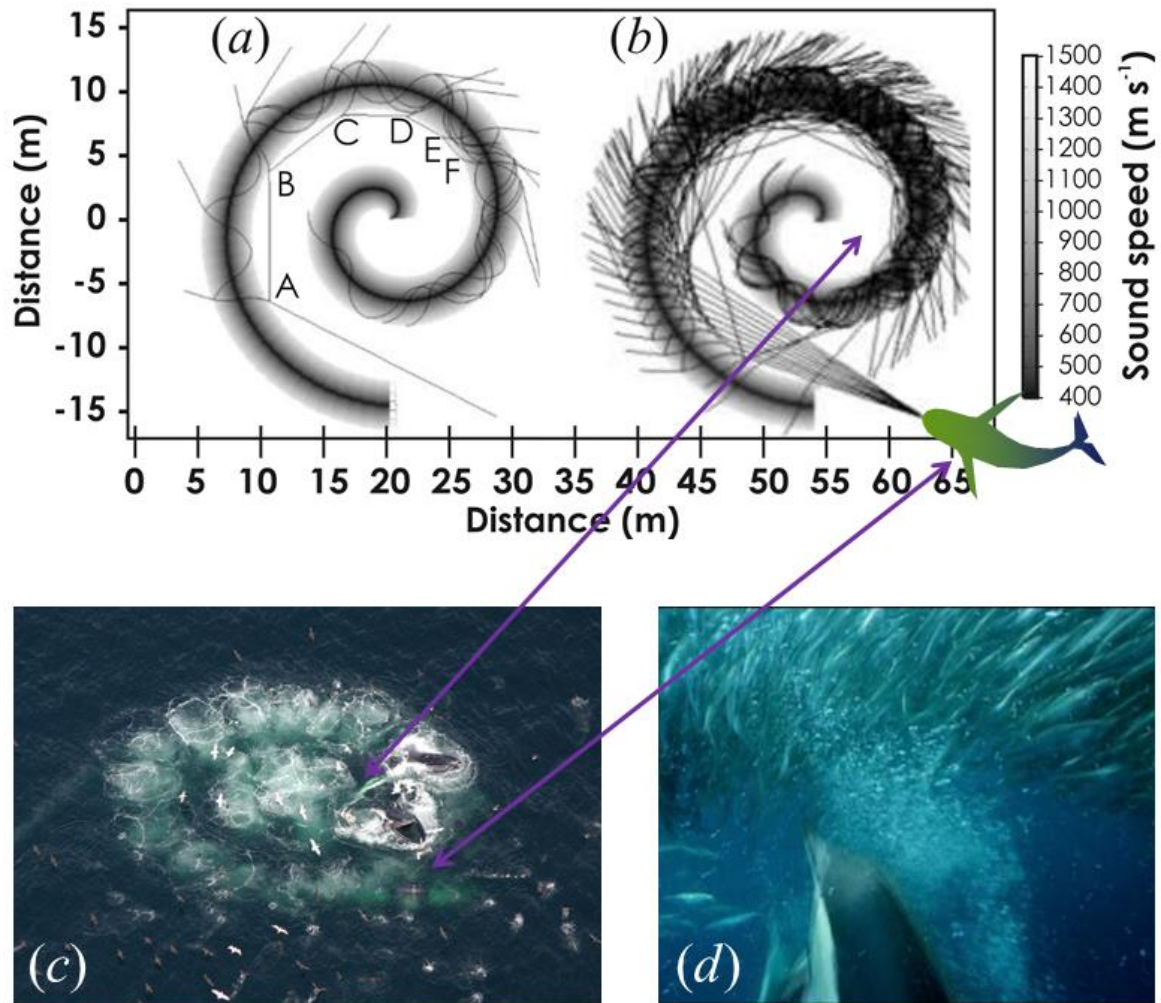


Figure 2. Modelling the acoustics of whales and dolphins when they use bubble nets for hunting. (a) A plan view 2D map models the bubble-induced variation in sound speed (shown in greyscale) that has been inferred from photographic evidence of spiral bubble nets produced by humpback whales. A single ray, projected into the open end of the spiral, impacts the bubbly wall in turn at A, B, C, D..., the grazing angle decreasing each time such that it does not propagate all the way to the centre of the spiral. At each impact with the bubble wall, the ray is partially reflected from the bubbly wall and partially transmitted into it, from which point refraction occurs. No absorption is included. (b) When many rays are modelled in this way, a 'quiet' zone is seen to occur at the centre of the net, walled-in by zones of high intensity. The photograph in (c) shows that this corresponds to the point at which whales rise from the water (purpose arrow connecting the locations of the source modelled whale and quiet zone) (photo by T. Voorheis of Gulf of Maine Production). (d) Image of a dolphin blowing bubbles to catch fish (Image courtesy of The Blue Planet, BBC). For details see Refs. [2, 31-33].

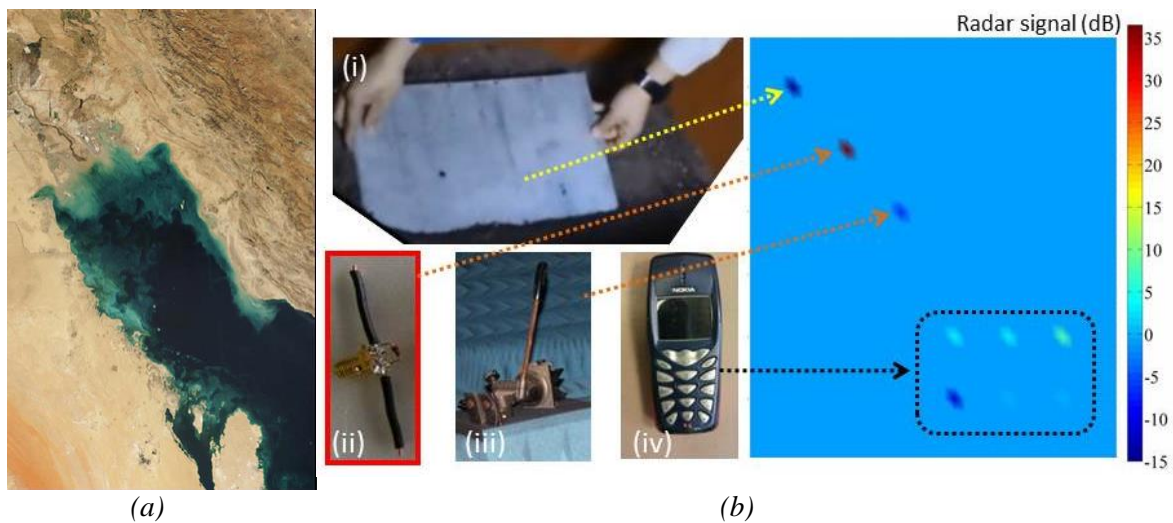


Figure 3. Scenarios where the use of two pulses to distinguish target from clutter would help (a) sonar and (b) radar. (a) Aerial image of Persian Gulf (image courtesy J. Descloitres, MODIS Land Rapid Response Team at NASA GSFC). (b) TWIPR Radar signal from (i) an aluminium plate, (ii) a circuit resembling components of a bomb trigger; (iii) a rusty bench clamp; (iv) mobile phones in various states: on, off, or with invalid SIM cards, which (along with differences in the radar resonance characteristic of the semiconductors with different models of phones contained within the dotted box) gives rise to different scattering strengths. The spatial layout of the colour map reflect the superimposition of different tests, because the test rig was not sufficiently large to lay out all targets simultaneously. See Ref. [30] for details.

4. 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 [2, 34] the possible sound of ‘methanefalls’ (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 4(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 4(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 4(c)), during descent some indication of topography that might have been carved by flowing surface liquid was revealed (Figure 4(d)), and later radar observations by Cassini revealed lakes (Figure 4(e)).

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. Despite all the planetary probes that have been sent out, we have not yet heard the soundscape of another world [35]. Consequently, this work was conducted for the purpose of:

- enabling better design of microphones and sound sources for use on future planetary probes, with respect to improving signal to noise ratios, more reliably interpreting any detected signals, and enabling and maintaining an appropriate calibration given the differences between Earth’s environmental parameters and the deployment environments (which can vary hugely even over a single world like Venus or Jupiter) [36-40];
- improving the design of missions exploiting acoustics in planetary exploration (for

example, by 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 [41-43]);

- eliminating errors in mission planning introduced by use of familiar Earth-based acoustics to extraterrestrial environments [38];
- 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 [44,45] (Figure 5).

For this latter objective, in designing the algorithms to simulate the sounds of worlds, we were able to provide a device, licensed to planetaria [44], 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 live and speak), when telling schoolchildren about that planet [46,47]. More details on this topic are available on the Internet [48].

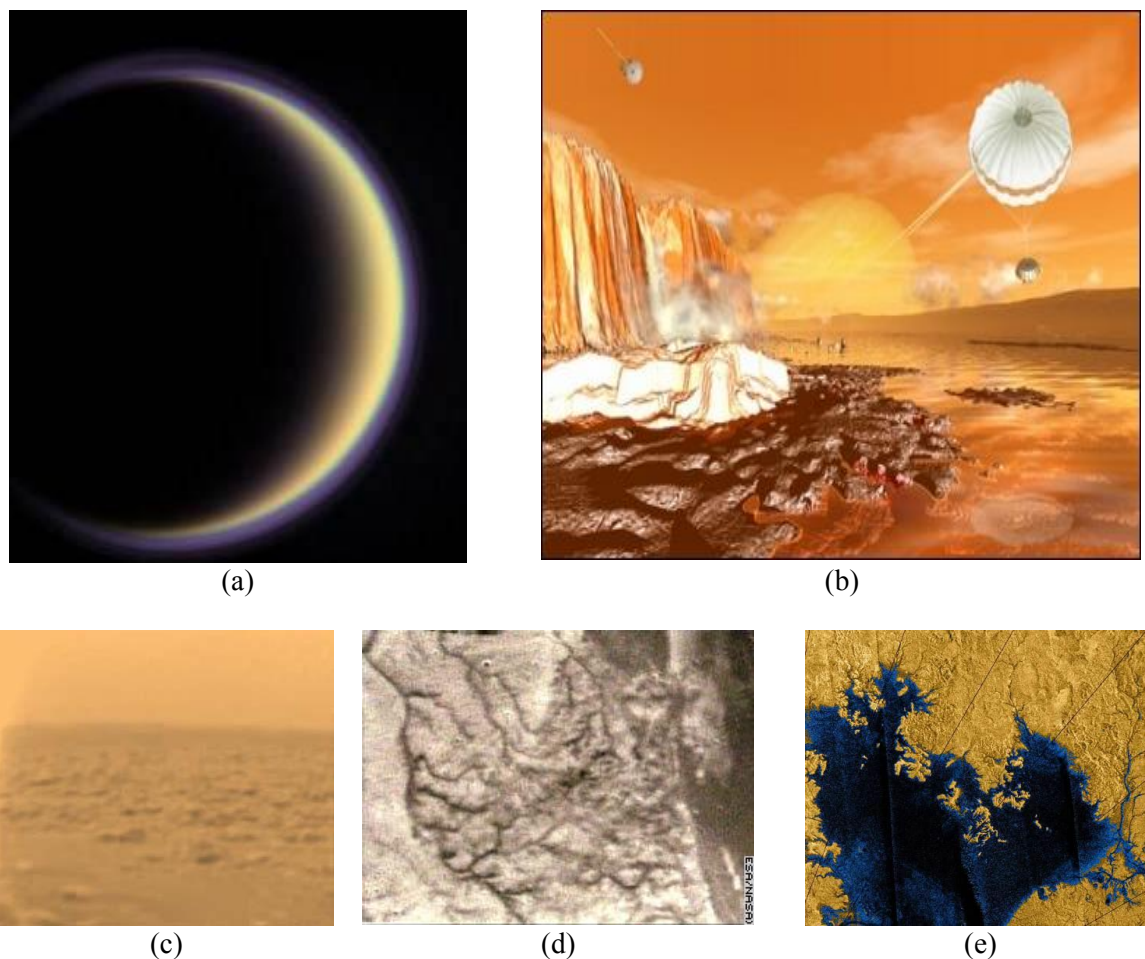


Figure 4. Images of Titan of relevance to the *Cassini-Huygens* mission. (a) Image of Titan. (b) Artist's impression of the *Huygens* probe parachuting through Titan's atmosphere, having previously detached from the *Cassini* vehicle (seen in the upper left of the image). (Painting by D. Seal). (c) The 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-colour *Cassini* radar image of Titan's surface. Blue colouring 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.

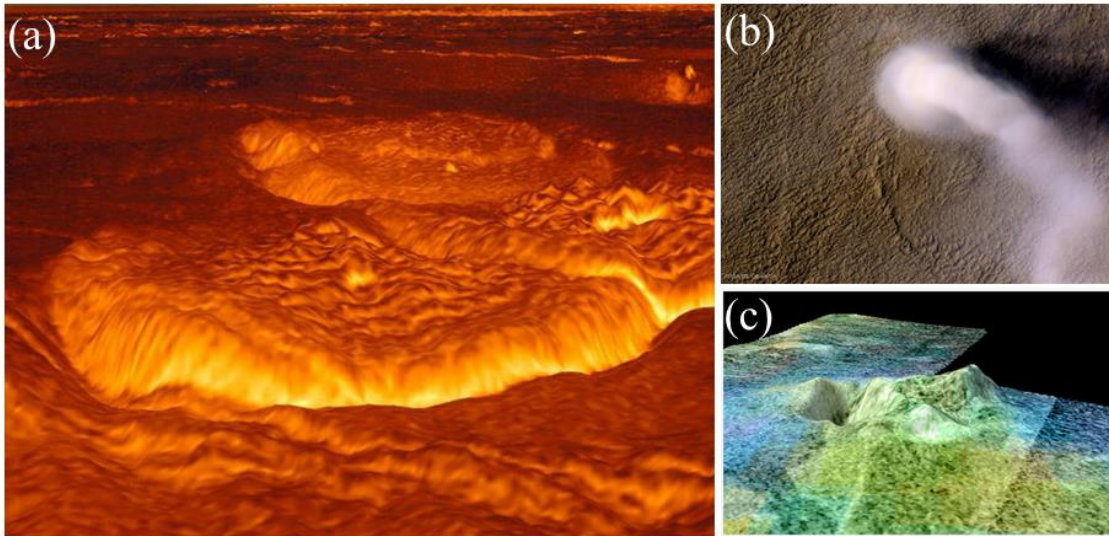


Figure 5. Extraterrestrial locations of interest for acoustical sensors. (a) A computer reconstruction of the surface of Venus, created from data from the Magellan spacecraft. Credit: E. De Jong et al. (JPL), MIPL, Magellan Team, NASA <http://www.space.com/18525-venus-composition.html> (b) Dust devil recorded by the HiRISE camera on board the Mars Reconnaissance Orbiter. Tracking across the flat, dust-covered Amazonis Planitia in the northern Martian spring of 2012, the core was about 140 meters in diameter. Lofting dust into the thin Martian atmosphere, its plume reaches about 20 kilometers above the surface. Tangential wind speeds of up to 110 kilometers per hour are reported for dust devils in other HiRISE images. Image Credit: HiRISE, MRO, LPL (U. Arizona), NASA.<http://apod.nasa.gov/apod/ap150303.html>. (c) False colour image of evidence for a possible cryo-volcano on Titan, photo credit, NASA, Cook *et al.* [49].

5. Cold water cleaning

4.1. The need for cold water cleaning

Efficient cleaning is central to modern life, from healthcare, to food preparation, to manufacturing and maintaining infrastructure [50,51]. This not only constitutes excessive consumption of one of our most valuable resources, but also generates large quantities of contaminated run-off. Uses range from the domestic to the exotic. Managing and purifying the water used in cleaning is a major issue because:

- the volumes of water used in cleaning are very great (e.g. it takes 100 tonnes of water to produce 1 tonne of clean wool after shearing [51]);
- purifying run-off is costly (e.g. each cubic meter of water used for cleaning in the nuclear industry costs £10,000 to treat subsequently [51]);
- even water that might appear not to be as grossly contaminated as the above two examples can present a hazard because of the volumes are high and run-off tends to travel into natural water resources (with detergents poisons, pesticides and herbicides from farmland and industry being carried into streams [52] where they can cause the demise of fish populations [53]).

Policymakers, the public and industry need to act to future-proof society against future problems caused by the extensive use of water in cleaning. Already, inadequate cleaning produces severe public health issues in hospitals [54, 55]. From major factories in the industrialized world to the local abattoir in the developing world, the mismatch between the volumes of water and additives used, and the robustness of the water supplies on which we depend, is failing to do its part in mitigating against future crises in water supplies, food production, and healthcare [56].

4.2. *The Ultrasonically Activated Stream*

One particular innovation was the Ultrasonically Activated Stream (UAS, invented at the University of Southampton and now in production by Ultrawave Ltd. under the name StarStreamTM), which enhances the cleaning ability of liquids, and in particular enables cold water cleaning. The UAS system, like the ultrasonic cleaning bath, bases its cleaning action on the speed of the bubble wall motion, and not (like pressure washers) on the speed of the flow. As such it will be less damaging. The UAS system produces a free flowing liquid stream, each nozzle generating flows of around 1-2 litres min⁻¹. Here the cleaning action of bubbles, excited with a suitable ultrasonic field, is generated at the end of a fluid stream. In addition, low flow rates of fluid within this approach are useful in releasing the contaminant from the surface and avoiding re-deposition at another location (a further possible limitation in bath geometries). Using higher frequencies and generating lower amplitudes of ultrasound in air than cleaning baths, StarStream has not had any reports of the 'subjective' adverse effects (headaches, nausea, tinnitus, migraine etc.) anecdotally attributed to some other sources of ultrasound in air, including some (but by no means the majority of) users of ultrasonic cleaning baths [57]. The low velocity stream approach has many advantages; however, two basic criteria are necessary for this strategy to be successful. First, the sound field must be sufficient to generate bubble activity at the solid/liquid interface of the material to be cleaned. Second, a suitable bubble population must also be present on the surface of the target that needs cleaning. This population can then be driven by the sound field deployed and act on the contaminant at the interface in question (through suitable oscillation [58-61] and shear forces). These two requirements are by no means trivial to create within a flowing stream but this has successfully been achieved in the UAS system.

The UAS system in some ways brings the power of an ultrasonic cleaning bath to the end of a hose, so that items can be 'cleaned in place'. Both the UAS and the ultrasonic cleaning bath replace the pressure and flow that comes purely from the stream of water in the pressure washer, with pressure and flow close to a bubble wall. However, it would not be correct to equate the bubble activity in the cleaning bath with that which occurs in the UAS. The ultrasonic cleaning bath causes cavitation, whereby bubbles collapse under pressure fields to generate extreme conditions [62-64], which can include the generation of free radical generation [65, 66] and strong pressure waves [67-68] from the gas compression, although significantly more powerful ones can occur in the blast waves launched when collapsing bubbles involute to form microjets [69-72]. Pressure waves and jet impact can remove material from surfaces [71, 73]. In contrast, the UAS system projects sound down a column of water [74] in order to excite surface waves [75] on the walls of microscopic bubbles on the surface to be cleaned. These surface waves can generate convection [76-79] and shear forces [80, 81] in the liquid close to the bubble wall, and so produce a cleaning effect, and alter the way material deposits onto surfaces [82].

The design, construction and operation of the UAS device are detailed elsewhere [83], but the basic principle is that cold water is fed into a hollow horn that contains an ultrasonic transducer operating in excess of 100 kHz. The ultrasound and microbubbles in the flow both travel down the stream of water to the target that is to be cleaned. If the bubbles are ultrasonically activated when they are on the target, the cleaning ability of the liquid is enhanced in four ways (figure 6):

- The bubbles are attracted to the surface to be cleaned by Bjerknes radiation forces [84], and are not as rapidly washed away by the flow as they would be in the absence of ultrasound.
- The bubbles are particularly attracted into crevices by secondary Bjerknes radiation forces [84]; such crevices are traditionally more difficult to clean by wiping or brushing.
- Surface waves on the walls of the bubble, excited by the ultrasound, produce enhanced convection in the liquid and enhanced shear in the contaminant, causing its removal.
- The progress of the bubble into the crevices would, if the liquid contained additives (e.g. detergent or biocide) cause that additive to penetrate the crevice far more rapidly than would reliance on simple diffusion, so that cleaning can potentially be achieved more rapidly, and with lower concentrations of additives.

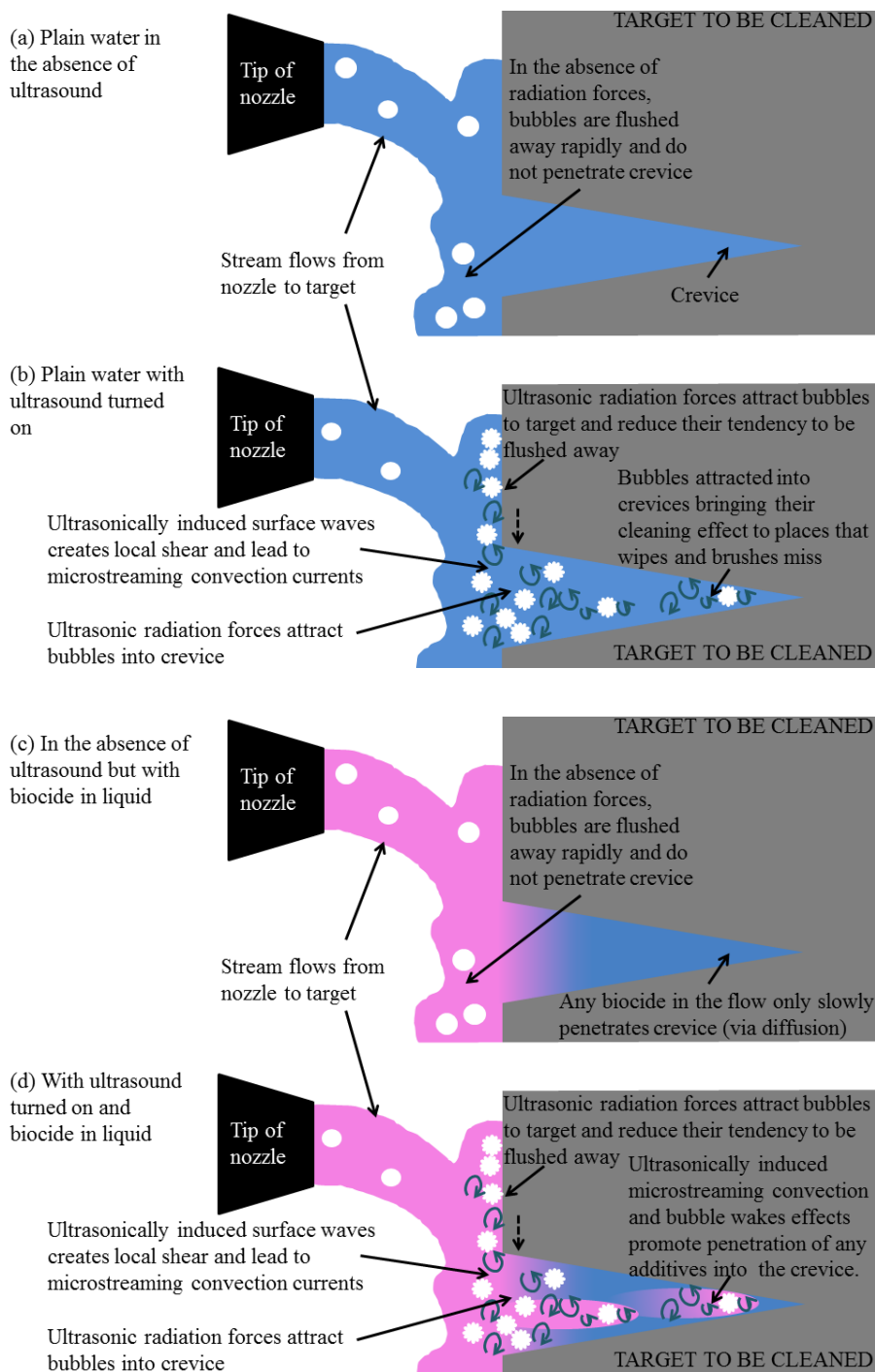


Figure 6. Schematic comparing the behavior of bubbles emitted from a StarStream device, for cases when: (a) no ultrasound is used, and the water contains no additives; (b) the water contains no additives, but the ultrasound is activated; (c) no ultrasound is used, and the water contains additives (in this case, biocide); (d) the water contains additives (in this case, biocide) and ultrasound.

The effectiveness of the UAS system has been demonstrated in controlled tests on particularly difficult problems, specifically on:

- the cleaning of brain tissue and prions from surgical steel, the removal of contaminating material from bone transplants [85];
- the removal of biofilms of dental bacteria [85, 86];
- the cleaning of skin models [85, 87];
- the cleaning of marine biofoulant [88];
- the cleaning of railway track [89];
- the cleaning of hands, kitchen surfaces, tools, glue from jar labels, contaminated tubes, and components of railway locomotives [90].

Here a range of other applications are shown. In all of them, the UAS system was a commercial StarStream device that projected, into the liquid stream, only cold water directly from the mains water supply, without additives or heating, at a flow rate of around 1 litres per minute.

Figure 7 shows how StarStream enables cold water, without additives, to remove mascara makeup from a metalworker's file. Figure 8 shows removal of whiteboard marker from a hand by StarStream using just cold water with no additives. Figure 9 shows the removal of a layer of VaselineTM petroleum jelly (beneath which was a layer of lipstick, added to provide a visual cue for the removal of the VaselineTM).

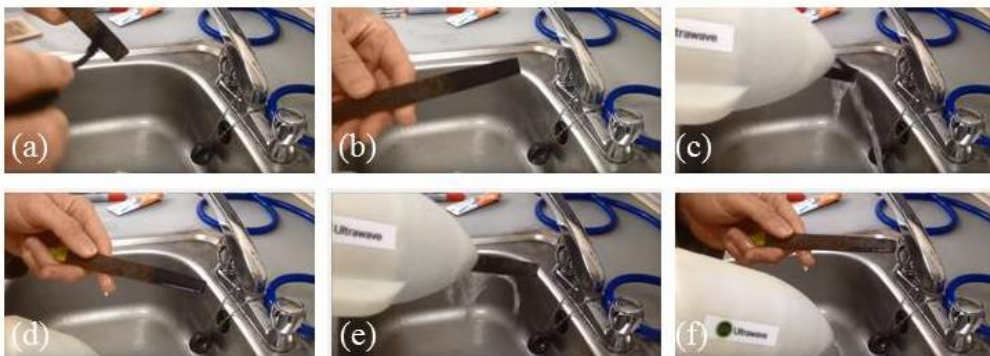


Figure 7. Cleaning a workbench file using UAS. (a,b) A workbench file has mascara make-up smeared onto it. (c) A StarStream device – with the ultrasound turned off - passes a stream of cold water with no additives over this contaminant, and afterwards (d) there has been no observable cleaning. However, when (e) the same water stream has ultrasound added to it, then afterwards (f) both the contaminant has been removed. The panels are stills from the video available at: <https://www.youtube.com/watch?v=22tUGEGyk10>



Figure 8. Cleaning whiteboard marker off a hand using UAS. (a) A line of red whiteboard marker is applied to a hand, but (b) when a StarStream device – with the ultrasound turned off - passes a stream of cold water with no additives over this contaminant, no observable cleaning occurs. However, when (c) the same water stream has ultrasound added to it, then the hand is cleaned. The panels are stills from the video available at: <https://www.youtube.com/watch?v=ElxcBn7-t8s>

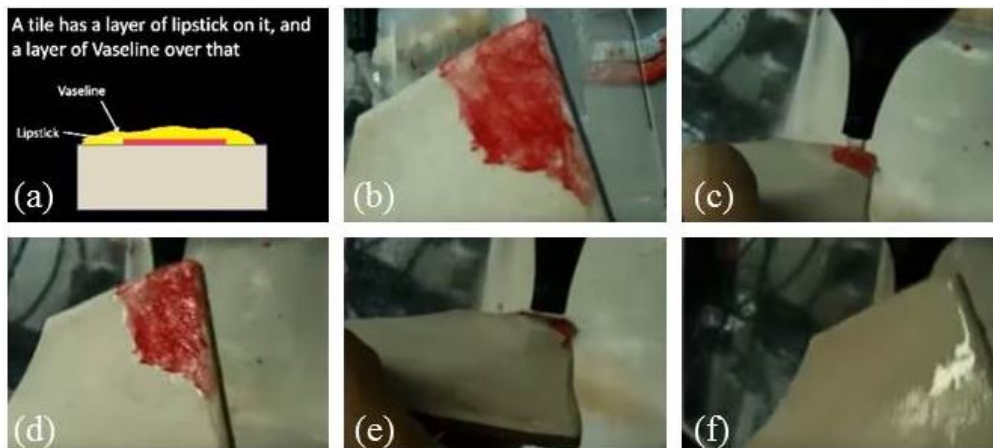


Figure 9. Cleaning lipstick, covered by a protective layer of VaselineTM, using UA. (a,b) A ceramic tile (10 cm x 10 cm) has lipstick placed on one corner, and a layer of VaselineTM petroleum jelly placed over the lipstick. (c) A StarStream device – with the ultrasound turned off - passes a stream of cold water with no additives over this double contaminant, and afterwards (d) there has been no observable cleaning. However, when (e) the same water stream has ultrasound added to it, then afterwards (f) both layers of contaminant have been removed. The panels are stills from the video available at: <https://www.youtube.com/watch?v=XZ2oe4XaM3Y>

4.2. Choice of device

There are many options for cleaning. Perhaps the most widespread for external use are domestic and small-industry power washers (also known as pressure washers) which pass water (usually with additives) at high speed onto the surface to be cleaned. Contaminants are flushed away (so that unlike systems that clean immersed targets, the object to be cleaned is not immersed in a ‘soup’ of contaminated liquid). The down-side to this is that power washers use large volumes of liquid (up to 20 litres per minute for a large pressure washer), and consequently lead to large volumes of contaminated run-off. Pressure washers are effective, and if resources are significant (for example, on a warship or on a train) they can always be scaled up to produce enormous pressure. As a result, in assessing the performance of a pressure washer against any alternative, the first question is not ‘which cleans best’ but rather ‘can I tolerate the pressures, splashback, aerosol, run-off and potential damage that the candidate pressure washer might produce?’.

On the domestic or small-business scale, pressure washers are difficult to scale up (in terms of using multiple nozzles or larger nozzles), both because of the pump requirements (in terms of power and water usage), and because they generate considerable back force when used, meaning that the structural support for scaled up versions must become increasingly robust. Indeed, even on major infrastructure like the railways, although pressure washers can be used to try to mitigate the effect of ‘leaves on the line’, those washers are so powerful that they damage the track if used when the locomotive is stationary, and when in normal use (with the locomotive moving) they can damage the locomotive from the stones that the pressure washers accidentally throw up, and the run-off can damage the banks on which the track sits. This challenge is discussed in more detail later.

Even small power washers can be damaging to delicate surfaces (a well-recognized mistake by boat owners who attempt to clean rope with pressure washers), and they generate aerosols of contaminated liquid (the liquid droplets produced when pressure-washing, say, sewage lines represent a significant hazard and route to spread contamination [51]). Whether the user cares about the backsplash, aerosol and spray generated by pressure washers, and the abilities of these to carry and redistribute contaminants onto nearby objects including the user (where they can be inhaled, settle on skin or eyes etc.), depends on the application. Applications where such phenomena might be of particular concern

include cases where the contaminant contains sewage, bacteria, radionucleotides, petrochemicals or chemical ingredients that represent an environmental hazard (e.g. marine antifoulant, microbeads etc.).

Pressure washers will entrain an *ad hoc* population of bubbles. There are many technologies advertised as enhancing cleaning by the addition of bubbles, often with size distributions constrained to certain small sizes [91-94] but without going to the trouble (in terms of instrumentation, power requirements etc.) of adding sound, begging the question of why one would ever wish to use an ultrasonic system, with its added complexity of needing to power an ultrasonic source.

The ultrasonic field does two things: it causes motion of the bubble wall (e.g. generating inertial cavitation in the ultrasonic cleaning baths, and surface waves with UAS systems); and it attracts the bubbles towards the solid and into crevices. Figure 10 compares the Primary Bjerknes force that attracts this bubble to the rigid wall, with the Mutual Bjerknes force which would be attractive between two bubbles whose centres are separated by the distance given on the horizontal axis (an unrealistic proposition for distance smaller than a bubble diameter). As expected [95, 96], the Primary Bjerknes force that attracts the bubble to the wall is many orders of magnitude greater than the other two forces: although it must in principle decrease to zero at the bubble wall, of course these numbers lose meaning within one bubble radius (here, 20 microns) from the wall. Coincidentally, this is roughly the distance from the wall at which the Mutual Bjerknes force (which in principle varies with distance from the wall as an inverse square law [96]) equals the buoyancy force on the bubble.

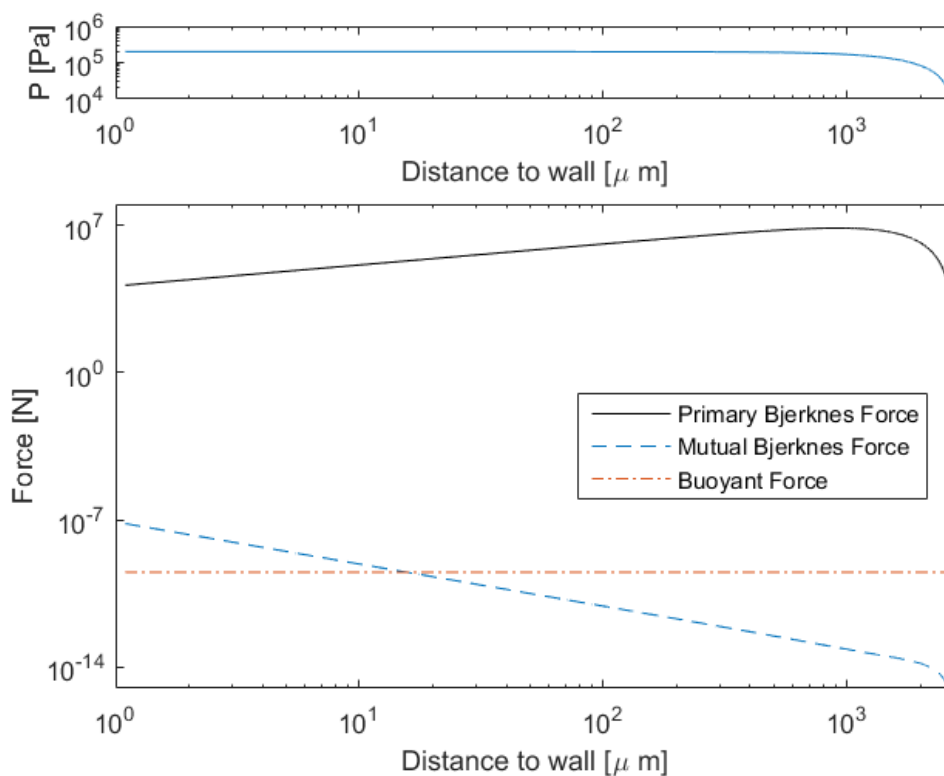


Figure 10. Comparison of pressures and forces acting on a bubble near a wall, plotted on a common horizontal axis that shows distance from a rigid wall (limited to within one quarter wavelength from the rigid wall). The upper panel shows the variation of the amplitude of the time-varying pressure, formed when a 135 kHz plane wave of amplitude 100 kPa is normally incident on the rigid wall. The lower panel compares the Primary and Mutual Bjerknes forces on an air bubble in water under 1 bar static pressure. The buoyancy force is shown for comparison. Note that both axes are logarithmic. The calculation assumes simple harmonic motion of the component of bubble motion that contributes to the zeroth order spherical harmonic perturbation of the bubble wall (in practice such high driving pressures will cause departures from this in this bubble).

The magnitude of the Primary Bjerknes force that attracts the bubble to the wall is impressively large, given that the water hammer pressure exerted by the flow of the liquid stream would be only 20-40 Pa, 100,000 less than the water hammer pressure from a domestic pressure washer. A pressure washer would of course not be capable of using that water hammer pressure as an active force to drive a bubble to a wall, as the Primary Bjerknes force does (and of course the acoustic radiation forces that attract bubbles to surfaces will increase if the wall is structured [97]). Therefore the radiation forces that attract the bubble to the wall are impressively high, but it is critically important to recall that these are the forces causing bubble migration; they must be distinguished from the forces that cause cleaning. The forces associated with the actual cleaning are then the shear forces close to the bubble wall produced by surface waves.

Addressing therefore the use of ultrasonically activated bubble activity in cleaning, the most well established device for cleaning using bubbles and adding sound, is the ultrasonic cleaning bath [98], which most frequently relies on an *ad hoc* bubble population. As an immersion system, it does not generate large quantities of run-off and can save time by bath-processing many units simultaneously. Such baths represent an established global product, but have many limitations which prevent further market penetration: the bath is too small for some objects (e.g. they cannot be used for vehicle cleaning); the bath cannot get into complex geometries and clean them (e.g. it cannot be used to hose down inside an engine); the item to be cleaned sits in a soup of contaminated liquid. Moreover, immersion of the object to be cleaned into the bath can degrade the sound field and the cleaning action [51]. This is not always apparent, since the monitoring of the cleaning performance of such ultrasonic baths is often rudimentary, much of industry eschewing new techniques in favour of a check based on the insertion of domestic aluminium cooking foil into the bath to see whether the cavitation is capable of generating small erosion pits and holes within the foil [98, 99]. The above list of potential drawbacks to ultrasonic cleaning baths is not exhaustive when considering a procedure such as hand washing: the ultrasonic bath works by generating violent bubble collapse, which may be destructive to tissue such as skin, and can penetrate tissue at bath frequencies.

Comparison of UAS to ultrasonic cleaning baths and pressure washers is illuminating, in that it shows that the question is less of how well a technology cleans, but more of in what scenario it can be used. Ultrasonic cleaning baths and UAS both use ultrasonically activated bubbles, but the mechanism by which they clean is very different, and this produces key observables. For example, one would never immerse a hand in an ultrasonic cleaning bath because the hazard of cell damage is high, and yet UAS has to date been shown to be safely used on hands (figure 8). One might therefore conclude that UAS uses a ‘gentler’ form of cavitation, and few would argue that Faraday waves represent a ‘gentler’ form of bubble activity than the inertial cavitation that the bath generates. However having settled on the label of ‘gentler’ cavitation, one must not confuse gentleness with effectiveness: in a recent study [89, 100], UAS was shown to clean off railway track, within seconds, the organic layer produced when leaves are crushed onto it, whilst ultrasonic cleaning baths were unable to remove such a contaminant, even after many minutes of immersion. In addition to the advantages established above (UAS could clean the track in place, whilst the track had to be cut in into sections small enough to fit into the bath, transported to it, and were immersed in it off line), UAS brought greater effectiveness in cleaning whilst also being (in tests to date) ‘hands safe’. This particular contamination is responsible for the ‘leaves on the line’ problem which costs the UK rail network £50M annually, as timetables are adjusted to reduce the speed of the trains to compensate for the decrease in braking ability that crushed leaf contamination causes.

Therefore comparison of these two ultrasonic cleaning methods provides fruitful discussions on effectiveness, whilst highlighting that there are particular scenarios to which one or other is suited (whilst the need to immerse targets brings many limitations to ultrasonic cleaning baths as discussed above, it does allow batch cleaning, and so can clean large numbers of small items more quickly than could a single UAS nozzle).

In contrast, there is little to be gained in comparing cleaning effectiveness of any system against that of the pressure washer, since the latter can always be scaled up, to the point where the most

powerful will cut through thick steel. The issue therefore is not one of how well each cleans, but whether the scenario will allow deployment. Can the user cope with the slow rate of covering an area that a single UAS nozzle requires? Can the user accept the surface damage, aerosol production, and use of electrical and water resources that come with the size of pressure washer that is required to achieve an acceptable level of cleaning? Does the need to ‘clean-in-place’ preclude use of an ultrasonic bath? Section 4.3 will explore a particular application, the cleaning of wounds and ulcers, where a UAS nozzle (which would generate water hammer pressures 100,000 less than those generated by the weakest domestic pressure washer) might make an interesting comparison with pulsed lavage system [101], particularly if low water and power requirements were to make them portable.

4.3. Implications for the cleaning of wounds and ulcers

As mentioned above, StarStream will enhance the efficacy of additives (e.g. detergents or biocides) in the penetration of cracks and crevices, so why demonstrate (in figures 7-9) its cleaning ability with just cold water and no additives? Some targets (e.g. lettuce [102]) can only tolerate cold water. In other circumstances (e.g. rural wound cleaning in a Low/Middle Income Country [LMIC]) cold bottled or packaged water might be the only clean water available [103].

Even in controlled hospital conditions in the developed world, wound cleaning is a major and unsolved issue. Considering just diabetics (which ‘is now the biggest cause of amputation’ [104]), the inability to treat ulcers properly creates a huge cost to patients and to the NHS. Discussing the care of diabetics in England, Kerr [105] states that: “Around 6,000 people with diabetes undergo leg, foot or toe amputation each year in England. Many of these amputations are avoidable.... Around 61,000 people with diabetes are thought to have foot ulcers at any given time, approximately 2.5% of the diabetes population... Only 50% of patients with diabetes who have had an amputation survive for a further 2 years. Even without amputation, the prognosis is poor. Only around 56% of people with diabetes who have had ulcers survive for 5 years... In 2010-11, the NHS in England spent an estimated £639 million–£662 million, 0.6–0.7% of its budget, on diabetic foot ulceration and amputation.” In particular, by calculating the excess bed days as the difference between the number of days that a procedure actually took and the number of days it would normally be expected to take, Kerr estimated that ‘expenditure on excess bed days in people with diabetic foot ulcers admitted to non-foot care HRGs is estimated at £100 million... The annual cost of non-amputation inpatient care for diabetic foot ulcers is estimated at £213 million’ (an HRG - Healthcare Resource Group - is grouping of patient events that consume a specified resource).

The impact of enhanced wound cleaning in the NHS that StarStream (or some other procedure) might provide could therefore be significant. However StarStream’s emphasis on the use of low volumes of cold water has other implications, notably because it turns cold drinking water (which on its own is not highly effective as a wound cleaner) into a more effective cleaner. If this enhanced cleaning ability translated through to wound cleaning, StarStream would have particularly applicability for those scenarios in which clean water is a scarce, because water is a dense commodity that has multiple uses. An army medic, or mountain rescue or catastrophe zone worker, might carry a limited amount of drinking water, but appreciate having the ability (when the need arises) to pass his/her remaining drinking water reserves through a battery-powered StarStream nozzle (perhaps with powder added first to make saline) in order to clean a wound for a few minutes. Battlefield and catastrophe zone wounds can be extremely hazardous, and sepsis can set before the victim arrives at hospital. Cleaning the wound first can reduce that hazard. Ambulances, rescue vehicles, small boats, helicopters etc. could all carry such items. Of course, for much of the world the prospect of transportation to a modern hospital is remote even for as predictable an event as rural childbirth in peace time [106], and in much of the world healthcare needs are made less predictable and manageable by accident, migration, conflict, resource shortages and infrastructure that is poor or overwhelmed.

Sepsis is indeed a huge problem: Severe sepsis hospitalizations are currently doubling each decade, resulting in at least 750,000 persons affected annually in the United States [107, 108], and 500,000

patients with severe sepsis are treated annually in US emergency departments [109], 100,000 of which are children [110, 111]. In one study, 27.1% of a set of 56,673 adult admissions to Intensive Care in England, Wales and Northern Ireland between 1995 and 2000 met severe sepsis criteria within the first 24 hours [112]. These admissions accounted for 45% of the total usage of the intensive care unit, and 33% of the hospital bed days used by all intensive care unit admissions. Of these, 35% died before being discharged from the intensive care unit, and the proportion that died at some point during their hospital stay was 47% [112]. Another study evaluated 28,150 patients with severe sepsis and septic shock, from January 2005 through February 2010, and found that in-hospital mortality was 29.7% for the cohort as a whole [113]. This percentage includes 17,990 patients who received antibiotics after sepsis identification. Expert consensus suggested that every 1 hour delay in effective therapy decreases survival by around 6%, and the Surviving Sepsis Guidelines mandate that intravenous antimicrobial therapy must be administered within 1 hour of recognizing septic shock [113, 114-119].

What has this to do with cold water cleaning? The above Surviving Sepsis Guidelines are challenging to implement [120]. Levy *et al.* [121] analysed data from 165 hospitals treating over 15,000 patients with septic shock and revealed that only 68% of patients received broad-spectrum antibiotics within 3 hours of presentation at the Emergency Department. However, sepsis is often not caused by infection (and so will not respond to antimicrobial therapy). Even if it is caused by infection, those infections may be fungal or viral, and not respond to antibiotics. Therefore the pressure outlined above to apply a broad-spectrum antibiotic may produce possible unwanted effects (such as suppression of the gut microbiome), could displace the required therapy that would be used had the cause of sepsis been properly identified, and will promote the development of Antibiotic Resistance. Cleaning wounds on-site, before transport to hospital, might therefore have wider benefits than simply reducing the hazard of sepsis in the patient – on a large scale it is a tactic to mitigate against the development of AntiMicrobial resistance (AMR), which is an arms race against natural selection that cannot be won [50]. To mitigate against potential catastrophes in healthcare and food production (which currently relies upon antibiotics to farm sufficient livestock to feed large tracts of the world), measures over and above the development of new antibiotics must be undertaken [50]. Two key elements of this are:

- infection prevention - if the microbe never enters the body, no antimicrobial is required;
- the removal of environments that encourage resistant strains to develop: the longer microbes are allowed to persist on surfaces involved in food preparation, infection management and water and waste treatment, the increased their chance of developing resistance and/or transferring it between microbes.

Cleaning is key to both these elements, and applies not just to hospital infections. To take just one example, despite all efforts, the UK population persists in washing their hands lamentably short of the recommended 20 s in warm soapy water. The past decade, and more, has shown that we cannot change the behaviour of sufficient numbers of people with campaigns to educate them on hand washing: the StarStream philosophy would be that, if we cannot change the behaviour, we change the water, making any shorter washes in cold water as effective as they can be.

StarStream cleans by a mechanical scrubbing action, which is very different to the chemical attacks that microbes are often challenged with, so giving another route to combat AMR. A major problem is that such agents enter the environment (the water supply, sewage, run-off etc.) where their occurrence aids the development of AMR. Microbe populations can become resistant because traditional chemical routes to cleaning leave ‘smoking guns’ in our water run-off, giving clues as to what was used to kill the previous generations of microbes. These ‘clues’ in sub-therapeutic concentrations might assist the vast reservoirs of microbes in our water and sewage systems to develop resistance. With StarStream, not only can we clean well, but nothing enters the run-off except the material we rinse off – there are no chemical clues that are flushed into the environment that microbe populations can use in the development of AMR.

The implications go further. The scenario raised above, of rescue personnel and vehicles needing to conserve the volume of water they carry but undertake adequate wound cleaning, will be even more

pertinent in a decade, when the first responder in many incidents is likely to be a drone. With its powerful battery but limitations in the amount of liquid it can carry, a drone makes an ideal test scenario for UAS: whilst it would be logical for a drone to carry a small amount of water to rehydrate a person needing assistance, a trade-off would normally need to be made between carrying liquid for rehydration and carrying liquid for wound cleaning. The ability to undertake cold water cleaning with water that could otherwise be used for rehydration ameliorates the conflict inherent in the choice of which liquid to carry. Indeed, by making drinking water dual-use (for rehydration and wound cleaning), there is impetus to build not-for-profit battery-powered reusable UAS nozzles that can fit on the top of any bottle of drinking water, for those parts of the world (in rural clinics, maternity units etc.) where bottled water represents the only source of clean water: UAS would turn such water from being a mediocre wound cleaner into a greatly enhanced one (Figure 11).

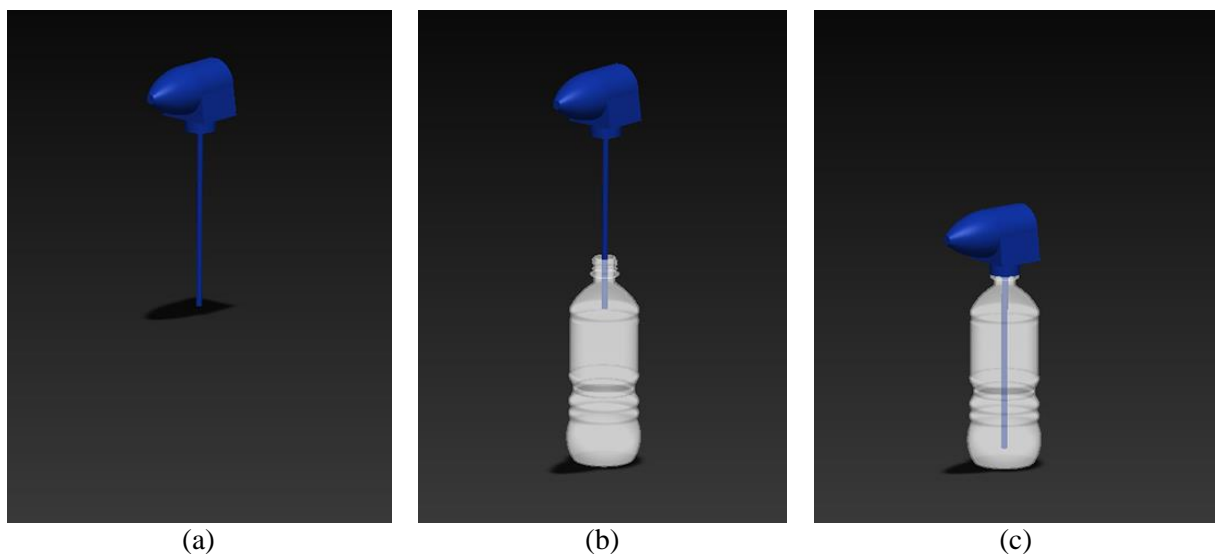


Figure 11. Concept for a battery-powered solar-charged UAS device that can fit onto any bottled drinking water unit. For the video see <https://youtu.be/o903Yey71L4>

6. Conclusions

The interaction of bubbles with acoustic fields provides a route by which fundamental research, covering physical, engineering, zoology, biophysics and biomedicine can be conducted and translated through to benefit society.

A key opportunity for bubble acoustics is in cold water cleaning, and its potential to address AMR. Unless preventative measures are found (and no-one in the world currently knows what those will be), AMR will (through the colloquial ‘rise of superbugs’) by 2050 be killing more people than cancer, and cost the world economy more than the current size of the global economy. We will not be able to feed the world unless we wean our food production industry off its dependence on antibiotics; common medical procedures (minor surgery, childbirth) will become significantly more hazardous; and advances in treatments (such as those for childhood leukaemia) will become reversed.

To offset this doom, the benefits for finding these preventative measures now would revolutionise current healthcare, the example given here being of the revolution to rural childbirth, wound treatment and childbirth, and the cost of amputations in diabetics.

Acknowledgements

The literature search for AMR contained in section 4.3 was funded by EPSRC's Network for Antimicrobial Action 'Bridging the Gap' grant NAMRA (EP/M027260/1), and by the University of

Southampton Strategic Research Group NAMRIP <http://www.southampton.ac.uk/namrip/index.page?>. The author is very grateful to Craig Dolder and Mengyang Zhu for assistance in generating figure 10, and to Dr Dolder for drawing figure 11 at the author's request, and for animating it: the animation, and other data from study are openly available from the University of Southampton repository at is <http://dx.doi.org/10.5258/SOTON/400818>.

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