The use of extra-terrestrial oceans to test ocean acoustics students

T. G. Leighton[a)]
Institute of Sound and Vibration Research, University of Southampton, Highfield, Southampton, SO17 1BJ, United Kingdom

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The existence of extra-terrestrial oceans offers the opportunities to set examination questions for which students in underwater acoustics do not already know the answers. The limited set of scenarios in Earth's oceans that can be presented to students as tractable examination questions means that, rather than properly assessing the individual scenario, students can rely on knowledge from previous examples in assessing, for example, which terms in equations are large and small, and what numerical values the answers are likely to take. The habit of adapting previous solutions with which the student is comfortable, to new scenarios, is not a safe approach to learn, as it ill equips the future scientist or engineer to identify and tackle problems which contain serious departures from their experience. [DOI: 10.1121/1.3680540]

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I. INTRODUCTION

The derivation of the basic rules of ray tracing in ocean acoustic propagation (e.g., that raypaths follow arcs of circles if the sound speed varies linearly with depth) is one of the foundation materials for teaching ocean acoustic propagation. Questions that ask for this derivation, and then apply it to scenarios in Earth's oceans, are in the author's experience a staple of many examination papers on the topic. However the limited range of scenarios that can be provided for student-level exam questions from Earth's oceans means that much of the thoughtfulness can be replaced by rote learning, devaluing the test and, worse still, equipping these future researchers with a mindset that relies on tweaking past solutions to solve future problems, rather than providing the best solution to the problem. This paper compares typical Earth-based questions (Sec. II) with extra-terrestrial opportunities (Secs. III and IV).

II. EARTH-BASED CALCULATIONS

To begin, an example from Earth's oceans is used to illustrate the typical calculation students might be familiar with when going into an examination. The speed of sound (c, in meters per second) in the ocean is often characterized using one of a number of similar empirical equations resembling

$$\begin{aligned} c/c_{\mathrm{ref}} \approx\ & 1449.2 + 4.6T/T_{\mathrm{ref}} - 0.055(T/T_{\mathrm{ref}})^2 \\ & + 0.00029(T/T_{\mathrm{ref}})^3 + (1.34 - 0.010T/T_{\mathrm{ref}}) \\ & \times (S/S_{\mathrm{ref}} - 35) + \alpha P_{\mathrm{h}}/P_{\mathrm{ref}}, \end{aligned} \tag{1}$$

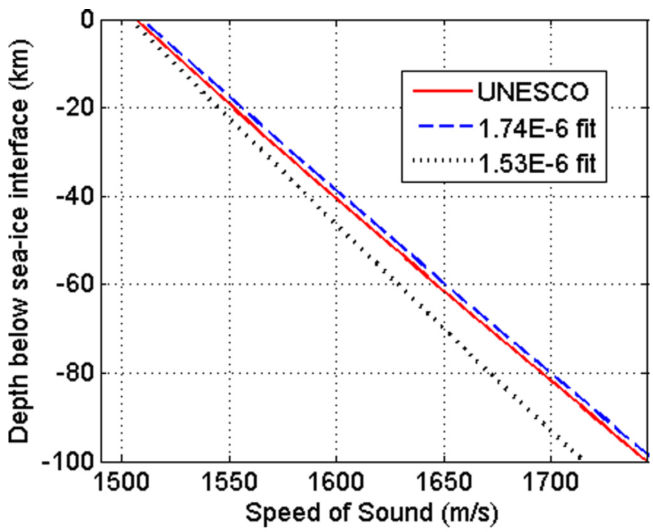
where c is a function of temperature (T in °C), salinity (S, in grams of dissolved salt per kilogram of sea water), and hydrostatic pressure P_{h} (which is measured in Pa, and excludes atmospheric pressure so that it is zero at Earth's ocean surface). The appropriate reference values are $c_{\mathrm{ref}} = 1\ \mathrm{m\,s^{-1}}$, $T_{\mathrm{ref}} = 1\ °\mathrm{C}$, $S_{\mathrm{ref}} = 1\ \mathrm{g\,kg^{-1}}$, and $P_{\mathrm{ref}} = 1\ \mathrm{Pa}$. There are many choices available for empirical expressions such as Eq. (1) to describe the effect of temperature, salinity, and hydrostatic pressure on the sound speed in the ocean. Equation (1) is generated by fitting a typical form of equation[1,2] to the so-called UNESCO equation.[3,4] In addition to being used to describe selected regions of Earth's oceans in this paper, Eq. (1) will also be used to set up models of Europa-type oceans. It is important to note that use of this equation here is to provide an examination question only: Data are currently lacking as to the extent to which Europa's actual ocean matches the conditions described in this paper. While the likely ranges of temperature and pressure on Europa can be estimated to be within the limits of applicability of a given formulation, the validity of using the range of Earth-based ocean salinities to describe the effect of the ionic content of Europa's ocean is unknown. The value of the fitting parameter α is especially important for deep water regions with small variations in temperature and ionic content. For the pressure range encountered across Europa's water column,[5] the value for the fitting parameter α which most closely matches the predictions of the UNESCO equation is $\alpha = 1.702 \times 10^{-6}$ (Fig. 1), and this value is also adequately accurate for the purposes of this paper to describe regions of Earth's oceans.

A cornerstone of ocean acoustics is the proof that, if the sound speed varies linearly with depth h (i.e., $\partial c/\partial h$ is a constant), then the raypaths follow the arcs of circles of radius R_{a} such that

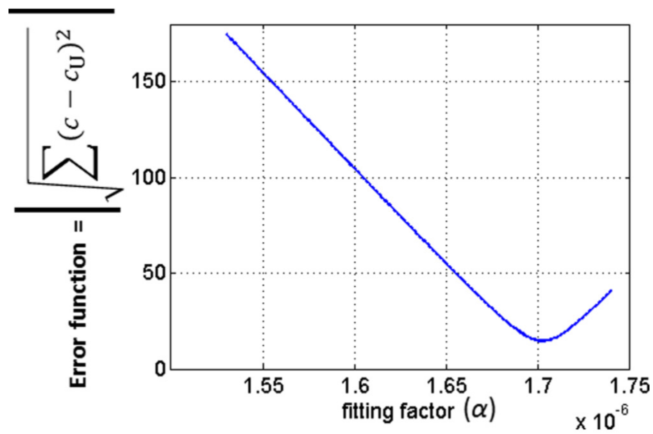
$$|R_{\mathrm{a}}| = \left|\frac{c_{\mathrm{H}}}{\partial c/\partial h}\right|, \tag{2}$$

where c_{H} is the sound speed when the ray is travelling horizontally.[1] This is the foundation of ocean acoustic ray tracing, since if the sound speed is assumed to vary with depth

[a)]Author to whom correspondence should be addressed. Electronic mail: tgl@soton.ac.uk



(a)



(b)

FIG. 1. (Color online) Predictions of the variation of sound speed with depth for a model Europa-type ocean, under the assumption that, at all depths, the ocean has a constant temperature of 4 °C and an ionic content which translates into Eq. (1) as though $S = 35\,\mathrm{g\,kg^{-1}}$. (a) The prediction of the UNESCO equation (solid line) is compared to those of Eq. (1) for example values of α of 1.74×10^{-6} (dashed line) and 1.53×10^{-6} (dotted line). (b) The error function between the sound speed predicted by the UNESCO equation (c_U) and that predicted by Eq. (1), c, as α varies, showing that the best fit is for $\alpha = 1.702 \times 10^{-6}$.

only over the region of interest (a frequent and convenient—although not always valid—assumption), then the sound speed profile (the plot of sound speed against depth) can be subdivided into thin adjacent horizontal layers, in each of which the sound speed is assumed to vary linearly. In addition to underpinning numerical ocean ray tracing, the above physics can also be utilized in examination papers by setting problems with analytical solutions. Taking an Arctic example, setting $S = 35\,\mathrm{g\,kg^{-1}}$ for convenience throughout the water column (to simplify the analysis for the student), and assuming for simplicity that the ocean temperature is 0 °C zero, then Eq. (1) predicts a dependence of sound speed on hydrostatic pressure only. Four assumptions make the problem tractable for simple examination questions (although, as will be seen in Sec. IV, all are questionable for Europa). These are that, with an assumed "flat Earth" geometry, the hydrostatic pressure P_h equals $\rho g h$ where ρ is the liquid density (assumed to equal $10^3\,\mathrm{kg\,m^{-3}}$ throughout this paper) and g is the acceleration due to gravity (assumed to be constant and, for Earth, equal to $9.8\ \mathrm{m\,s^{-2}}$). The linear variation of sound speed with depth is found from Eq. (1) to be

$$\partial c/\partial h \approx \frac{\alpha}{(P_{\mathrm{ref}}/c_{\mathrm{ref}})}\rho g \approx 0.01668\ \mathrm{s}^{-1}, \tag{3}$$

where the inclusion of the term $(P_{\mathrm{ref}}/c_{\mathrm{ref}})$ ensures dimensional consistency. If such a linear variation is provided through the use of a simplified ocean model, then the student can be asked for an analytical solution of example problems. For example, if a ray is projected horizontally from a sound source which is mounted on the seabed at 1 km depth, it follows the arc of the circle of radius

$$\begin{aligned}|R_a| &= |c_{1000}/\partial c/\partial h| \\ &\approx (1465.88/0.01668)\ \mathrm{m} \approx 87882\ \mathrm{m}\end{aligned} \tag{4}$$

(since the sound speed at $h = 1000\,\mathrm{m}$ is $c_{1000} = (1449.2 + 0.01668 \times 1000)\ \mathrm{m\,s^{-1}} = 1465.88\,\mathrm{m\,s^{-1}}$). Since the sound speed gradient is constant throughout the model water column, the ray will follow this arc all the way from the seabed to the top of the water column. Simple questions can be based on this geometry, such as using Snell's law to calculate that the acoustic ray meets the icepack at an angle of $\cos^{-1}(1449.2/1465.88) \approx 8.652°$ to the horizontal (assuming that details of the Arctic icepack mean that departures of the angle from the above, and of the sound speed at the top of the water column from the $1449.2\ \mathrm{m\,s^{-1}}$ given by inserting $h = 0$ into Eq. (1), can be neglected, assumptions that the students could be asked to justify if a further test was required). Knowledge of this angle can be combined with the value of R_a to calculate that the ray reaches the ice a horizontal distance of $R_a \sin\theta_1 \approx (87882\ \mathrm{m})\sin(8.652°) \approx 13220$ m from the sound source.

A variety of examination problems can be developed from these scenarios. For example, the vertical upward-looking beam of a sound source on the Arctic seabed will show variations in pulse travel time if a bolus of water of different salinity or temperature (in exam questions relating perhaps to melting icecaps) passes through a region of the water column and crosses the vertical beam. However the travel time associated with this beam contains limited diagnostic ability for the location and thickness of this bolus, and for the sound speed perturbation it causes, since there are too many variables to enable a unique inversion. However changes to the travel time and the locations where emissions from sidelobes reach the icecap can provide enough extra data to remove these ambiguities, and make interesting examination questions.

Similar questions can be based on simple models of the equatorial sound speed profile (with $S = 35\,\mathrm{g\,kg^{-1}}$ again assumed) where the sound speed profile in the assumed isothermal waters below depths of 1 km depends only on $P_h = \rho g h$, giving the same $\partial c/\partial h$ as in Eq. (3). At shallower depths than 1 km, the fall in temperature with increasing depth produces another sound speed gradient that the students can show to be approximately linear by differentiating Eq. (1) and assessing the size of the nonlinear terms before discarding them.[6,7]

The problem here is that (despite the sensitivity of such calculations to small changes) the students quickly become aware of the numerical values of the sound speed gradients and radii of curvatures they should be calculating, and know in advance which nonlinear terms can be neglected when differentiating Eq. (1) with respect to h, so that this is done without thought. Significant gradients in salinity (e.g., river outflows into deep water, or near estuaries, icecaps, and brine lakes) and temperature (e.g., hot springs) offer some limited variants in testing.

One solution is to ask the student to apply the above physics to extra-terrestrial seas. Data suggest that more than perhaps half a dozen[8] small worlds in the solar system contain water seas, as revealed by magnetometer data,[9] Schumann resonances,[10] and their response to tidal forces.[8] Some such seas have volumes exceeding that of all Earth's oceans combined. Examples are shown in Fig. 2. Section III considers an example based on acoustic propagation in the ocean of Jupiter's moon, Europa, which has been discussed in the context of a number of acoustical studies by various authors.[5,11,12]

III. CALCULATION FOR EUROPA

For the purpose of providing a tractable examination question, Europa can be assumed to have an outer radius of 1560 km, and an ocean consisting of a depth $H = 100$ km of water underneath a thickness $h_{ice} = 20$ km of ice (popular but not uniformly accepted dimensions[13]). Europa's acceleration due to gravity at its surface is $g = 1.31$ m s^{-2}. The question instructed those taking the examination that, despite the complexity of the physical chemistry in such an environment,[8,14] they could assume that the densities of the ice and water are constant at $\rho_{ice} = 920$ kg m^{-3} and $\rho_w = 1000$ kg m^{-3}, respectively, and that the ionic properties of the water throughout the water column could be assumed to give the equivalent effect of setting $S = 35$ g kg^{-1} in Eq. (1).

The illustrative question given here examines the following scenario. Using a nuclear heat source, a probe melts through Europa's 20 km ice sheet and travels to the seabed (assumed to be acoustically absorbent) to search for hydrothermal vents (since on Earth such vents can support life without reliance on solar energy; Fig. 2). The probe is designed to sit on the seabed, projecting an ultrasonic beam vertically upwards in order to send video to the module on Europa's surface. The probe accidentally lands on its side and the ultrasonic communications signal is projected horizontally, instead of vertically. This event is used to test a theory that the water temperature in Europa's ocean equals 0 °C at the seabed, and then rises linearly with increasing height above the seabed until it reaches 4 °C at height L above the seabed. The temperature above this thermal boundary layer is uniformly constant at 4 °C (although data are scarce, this is not the accepted temperature profile for Europa,[13,15] but one constructed to produce a tractable examination question). The sound speed profile will then differ from that shown in Fig. 1(a), but the student does not need to be supplied with such a graph, as only Eq. (1) is needed. Given these parameter values, the examination candidates were then asked to show that if the thermal boundary layer exceeds some critical thickness, the acoustic signal could (if sufficiently strong) be detected somewhere on Europa's surface.

The candidates were instructed that they could use some key assumptions. In addition to the assumption of $S = 35$ g kg^{-1} in Eq. (1) (despite the uncertainty as to the

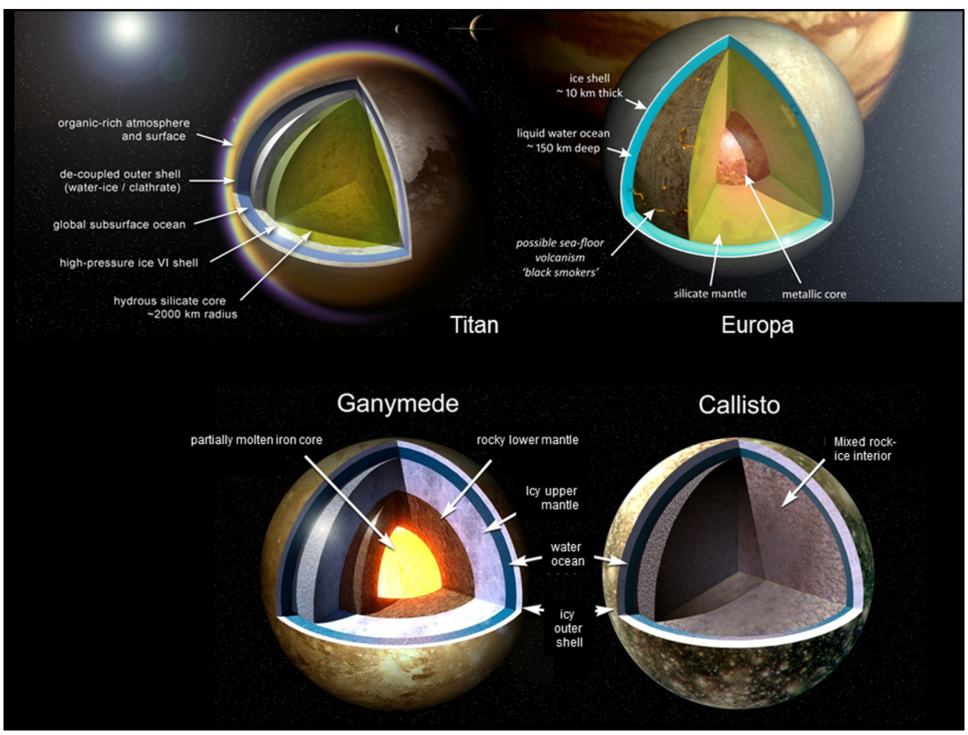


FIG. 2. (Color online) Schematic (not to scale) showing the supposed locations of water on three of Jupiter's moons: Ganymede (diameter ~5268 km), Callisto (diameter ~4800 km) and Europa (diameter ~3138 km); and Saturn's largest moon, Titan (diameter ~5150 km). Images created by A. D. Fortes, University College London.

ocean's ionic nature[9,13]) and the assumption that Europa's water and ice were taken to have the properties of standard seawater and sea ice that characterize Earth's oceans (taking, for example, no account of any differences in the crystalline phase on Europa), they were further instructed to model the acoustic propagation as if Europa were a flat world with a constant value of g, and to assume that the signal would have sufficient signal to noise ratio (SNR) to be detected were it to reach the base of the ice pack.

With these assumptions, the solution appears to be straightforward. The signal will reach the surface if the water within the thermal boundary layer is upwardly refracting. With increasing depth in this layer, the increasing hydrostatic pressure would tend to increase the sound speed, but the decreasing temperature would decrease it, and the ocean is upwardly refracting if the former effect dominates. At first sight in the boundary layer, the hydrostatic pressure can be expressed as

$$P_{\mathrm{h}} = \rho_{\mathrm{ice}} g h_{\mathrm{ice}} + \rho_{w} g h, \tag{5}$$

where h is the depth of the point of interest below the bottom of the ice sheet, and the temperature T (in °C) at a depth h (in m) below the surface of the water-ice interface is

$$T/T_{\mathrm{ref}} = 4(H-h)/L, \quad (H-L) \le h \le H. \tag{6}$$

Substitution of these depth-dependence expressions (5) and (6), along with $S = 35\ \mathrm{g\,kg^{-1}}$, into Eq. (1) gives

$$\begin{aligned} c/c_{\mathrm{ref}} \approx 1449.2 &+ \frac{18.4(H-h)}{L} - 0.88\left(\frac{H-h}{L}\right)^2 \\ &+0.01856\left(\frac{H-h}{L}\right)^3 + \alpha(\rho_{\mathrm{ice}} g h_{\mathrm{ice}} + \rho_{\mathrm{w}} g h)/P_{\mathrm{ref}}, \\ &(H-L) \le h \le H. \end{aligned} \tag{7}$$

In then calculating $\partial c/\partial h$, the student should be required to justify neglect of the contributions arising from the $(T/T_{\mathrm{ref}})^2$ and $(T/T_{\mathrm{ref}})^3$ terms in Eq. (7). This then gives the following linear approximation to the sound speed gradient:

$$\frac{\partial c}{\partial h} \approx \left(\frac{-18.4}{L} + \frac{\alpha \rho_{\mathrm{w}} g}{P_{\mathrm{ref}}}\right) c_{\mathrm{ref}}, \quad (H-L) \le h \le H. \tag{8}$$

(It should be noted that questions could be constructed where thermal gradients are sufficiently strong that the higher order thermal terms cannot be neglected.) For the boundary layer on Europa, the critical value for L occurs when $\partial c/\partial h = 0$, i.e., when

$$L = \frac{18.4 P_{\mathrm{ref}}}{\alpha \rho_{\mathrm{w}} g}, \tag{9}$$

where the term P_{ref} simply ensures that the expression is dimensionally consistent. Taking as a first approximation the acceleration due to gravity within the boundary layer to equal its value on Europa's surface ($1.31\ \mathrm{m\,s^{-2}}$), then assuming $\rho_{\mathrm{w}} = 1000\ \mathrm{kg\,m^{-3}}$ and $\alpha = 1.702 \times 10^{-6}$, the critical thickness of the boundary layer is approximately 8253 m.

The class could conclude that if the thermal boundary layer is narrower than about 8.25 km, then the thermal term $(-18.4/L)$ in Eq. (8) dominates over the hydrostatic term $(\alpha \rho_{\mathrm{w}} g/P_{\mathrm{ref}})$, and the sound speed in the thermal boundary layer decreases with increasing depth, and the layer is not upwardly refracting. For the signal to be detected somewhere at the surface in this "flat world" model, L must be sufficiently large (i.e., greater than around 8253 m) for the boundary layer to be upwardly refracting. A similar question could be set on a known boundary layer thickness but an unknown temperature at the seabed.

Many components of this answer are erroneous, as will now be discussed.

IV. FURTHER OPPORTUNITIES FOR USING EUROPA

The calculation given in the preceding section is simplified in a great many important ways to make it tractable as an examination question. Discussion of the limitations of the calculation can provide valuable opportunities for deeper understanding in the classroom, or for testing advanced students. Indeed the exam question explicitly stated what could and could not be assumed, since whilst some of the assumptions might be perceived by the most alert students to be erroneous, they are necessary to enable the moderate student to score moderate marks in a reasonable time.

Equation (5) [and consequently Eqs. (7)–(9)] arise out of the familiar equivalence that hydrostatic pressure is given by the product of liquid density (ρ_{w}), acceleration due to gravity (g), and depth within the liquid (h). It comes from integration over a change in r (a change in range from the center of the planet to the point of interest) of $\nabla P_{\mathrm{h}} = \rho_{\mathrm{w}} g$. Because Earth is so large, and human activities are usually confined to the outer shell of crust/ocean/atmosphere, the limits of the integration are far closer together than their distance from the center of the planet, and g can be assumed without significant error to be constant between these two limits. Such cannot be assumed to be the case on Europa, where the ocean accounts for over 6% of the planet's radius.

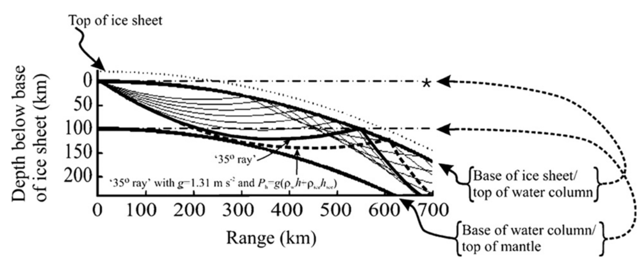


FIG. 3. Predicted ray paths within the curved model ocean of Europa, calculated for the conditions indicated in the text. The deepest of the selection of rays calculated in this way had a launch angle of 35° below the horizontal, and is plotted with a thick solid line, and labeled "35° ray." If the trajectory of the ray with a 35° launch angle were instead recalculated with the variation in gravity neglected, and the hydrostatic pressure calculated using rectilinear (as opposed to conic) sections, its trajectory would change to the one shown with the thick dashed line. The rays propagate within the upwardly-refracting water column, reflecting specularly off the sea/ice interface. To illustrate the error in geometry that a "flat world" assumption produces on Europa (quite apart from the error introduced in the calculation of hydrostatic pressure) the location of the ocean boundaries if curvature is ignored are also shown, using dash-dot lines. From Ref. 5.

Furthermore, the equivalence of ∇P_h with $\partial P_\mathrm{h}/\partial h$ (which leads to $P_\mathrm{h} = \rho_\mathrm{w} g h$) is not suitable since, on Europa, vertical lines at the points of interest are not parallel, the rectilinear geometry which is often used in deriving $P_\mathrm{h} = \rho_\mathrm{w} g h$ does not apply, and $\partial P_\mathrm{h}/\partial r$, not $\partial P_\mathrm{h}/\partial h$, should be used in place of ∇P_h. The effect on the ray paths of taking these effects into account is shown in Fig. 3. Interested readers are directed to read Leighton *et al*.[5]

If the boundary layer examination question posed in this paper were to be tackled rigorously, the fuller calculation would also have to take into account the curvature of the world, the non-zero beamwidth of any real echo sounder, the variation of densities of water and ice with depth, and the possibilities of reflection from the seabed and diffraction of the beam. Furthermore, detection of the signal, or failure to detect it, would not conclusively show that boundary layer model was correct or not, as other models had not been ruled out: is would simply show consistency with the above boundary layer model within the available data.

V. CONCLUSIONS

Europa offers a great many opportunities for questions, since the options for sound speed profile are numerous. Whilst some extraterrestrial bodies of water (e.g., in Enceladus) are unlikely to be sufficiently extensive to allow for considerable refraction, and hence are not good settings for calculations of the type described in this paper, they offer other options for acoustics-based questions for which the students does not have prior knowledge of the likely answer. A wide range[16] of acoustical phenomenon in gas, liquid and solid materials can be tested without *a priori* knowledge of the answer for extraterrestrial applications, including anemometry,[17] fluid loading,[18] sensing of accumulated mass,[19] fluid/structure interactions,[20] the generation of music and speech,[21] microphone design,[22] ambient noise,[23] ultrasonic range finding,[24] seep detection,[25] and fluid property measurement by acoustics.[26] Usefully for the examiner, the current lack of data on other worlds allows scenarios to be sufficiently simplified to make them tractable for the student, with appropriate wording to cover any future mismatch between the extant conditions and those assumed by the questioner.

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