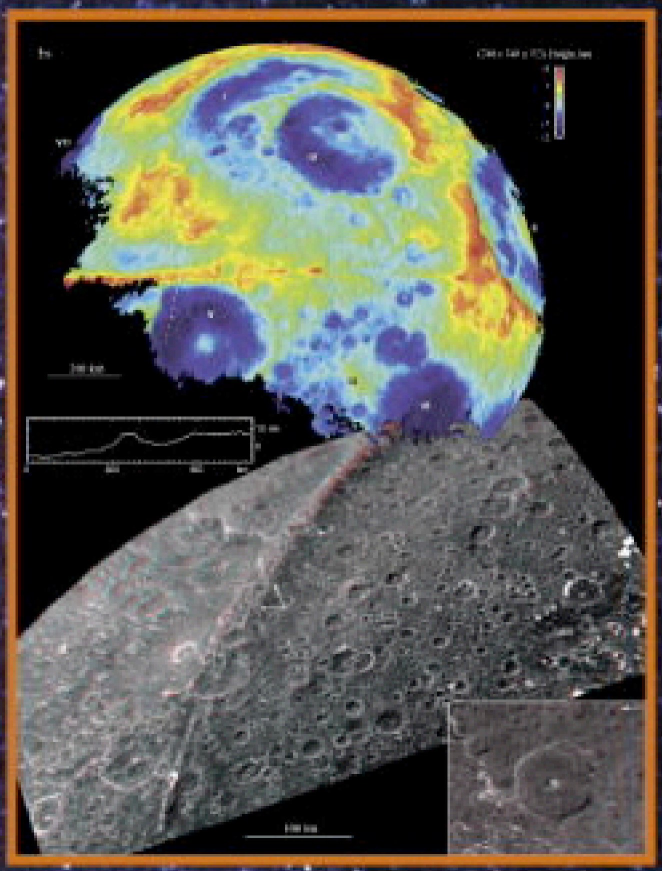
ISSN 0019-1035
This Number Completes Volume 193
Volume 193, Number 2, February 2008

ICARUS

International Journal of Solar System Studies



Published in Affiliation with the Division for Planetary Sciences, American Astronomical Society

Available online at www.sciencedirect.com
ScienceDirect
Icarus 193 (2008) 649–652
ICARUS
www.elsevier.com/locate/icarus

Note

The problems with acoustics on a small planet

Timothy G. Leighton *, Daniel C. Finfer, Paul R. White

Institute of Sound and Vibration Research, University of Southampton, Southampton, SO17 1BJ, UK

Received 25 May 2007; revised 28 September 2007

Abstract

In recent years increased attention has been paid to the potential uses of acoustics for extraterrestrial exploration. This paper concerns two aspects which should be taken into account when transposing terrestrial experience with acoustics to smaller worlds. These are, specifically, the effect on the acoustics of the variation of gravity with depth, and the curvature of the world's surface. A case resembling Europa is used quantitatively to illustrate these effects, indicating significant errors if these factors are neglected.

Keywords: Europa; Geophysics; Impact processes; Interiors

1. Introduction

In recent years increased attention has been paid to the potential uses of acoustics for extraterrestrial exploration. Acoustic systems offer several appealing features: the instrumentation is light-weight, low-power, and rugged (Muir, 2007; Leighton, 2007).

Traditionally, extraterrestrial acoustical investigations have been dominated by the modelling of low-frequency acoustic-related waves in, for example, planets (Lee, 1993) and stars (Elsworth et al., 1990; Rammacher and Ulmschneider, 1992; Bouchy et al., 2005); and in dust plasmas such as occur in planetary rings, comets and noctilucent clouds (Verheest, 1993; Pieper and Goree, 1996; Rosenberg and Kalman, 1997; Merlino, 1997; Shukla, 2000; Gupta et al., 2001).

Direct acoustical observations are understandably rarer (Delory et al., 1998; Zarnecki et al., 2005). With an appropriate propagation model (Petculescu and Lueptow, 2007), the received acoustic signal can be interpreted (inverted) to estimate the properties of the source and the propagation path. For probes which transmit and receive artificially-generated acoustic pulses, the source is well known and the interpretation reveals details of the propagation medium. This might range from inferring atmospheric sound speed from time-of-flight measurements over a few cm (Lebreton et al., 2005) to, speculatively, propagation around entire planets (Leighton et al., 2006, 2007), a technique which has proved to be very successful on Earth (McDonald et al., 1994; Mikhalevsky and Gavrilov, 2001; Wage et al., 2003). If the source of sound is natural, the power requirements and complexity of the hardware in principle become simpler. However the inversion discussed above now contains an extra cause of uncertainty (i.e., the characteristics of the source).

Some probes have carried microphones (Ksanfomality et al., 1983a, 1983b; Lebreton et al., 2005), and there have been spectacular successes from such missions in collecting data from a wide range of sensors (Zarnecki et al., 2005; Tokano et al., 2006; Stofan et al., 2007). However there are as yet no published results of in-depth interpretation and inversion of the natural acoustical signals generated by the extraterrestrial environment in order to characterise that environment (Fulchignoni et al., 2005a, 2005b, 2006; The Planetary Society, 2007, www.planetary.org/explore/topics/saturn/titan_sounds.html). Nevertheless our understanding of acoustics is sufficient not only to predict the natural acoustic surroundings (including the soundscape which would be audible to human hearing), but also is capable of generating methods by which acoustic data might be quantitatively inverted to characterise the environment (Leighton, 2004; Leighton and White, 2004; Leighton et al., 2005, 2006).

Several notable acoustical investigations feature Europa, a main objective being exploration of ways to characterise the ocean which could be present beneath the surface ice. Kovach and Chyba (2001) and Lee et al. (2003) produced pioneering studies which modelled acoustic propagation in the ice and the sub-ice ocean of Europa. They opened the way for assessing Europa's ice and ocean using acoustical signals of opportunity, generated by natural processes in the ice, ocean or mantle (Crawford and Stevenson, 1988; Schenk and McKinnon, 1989; Hoppa et al., 2000; Greenberg, 2002; Lee et al., 2005; Nimmo and Schenk, 2006; Panning et al., 2006; Leighton et al., 2006). An example application is where 'the spacing of arrivals in time can be used to robustly estimate source range' (Makris et al., 2001; Makris, 2001).

In order to define the required propagation model for acoustic inversion, it is efficient to transpose our well-established terrestrial models to these extraterrestrial environments (Lee et al., 2003). This paper highlights two factors which have not previously been considered in ocean acoustic propagation on Europa, but which become important when such transpositions are made to smaller worlds from Earth (with its relatively large radius, of which the oceans make up a tiny percentage) for long-range propagation. These are, specifically, the effect on the acoustics of the variation of gravity with depth, and the curvature of the world's surface. Whilst it is recognised that there remain uncertainties as to the nature of the ocean on Europa, a simple model (which resembles the generally-

---

* Corresponding author. Fax: +44 23 80 593190.
E-mail address: tgl@soton.ac.uk (T.G. Leighton).

0019-1035/$ – see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2007.10.008

accepted conditions on Europa) is used to estimate the magnitude of the effects on propagation. It is shown that these effects are general and not confined to specific ray paths, and furthermore that they are significant (compared to the precisions quoted in the earlier papers for propagation ranges used in those earlier papers). Future modelling over such ranges should therefore include this physics.

2. Theory

Consider a small spherical world of outer radius $R_{\mathrm{outer}} = 1561$ km, where a layer of ice (of thickness $h_{\mathrm{ice}} = 20$ km and bounded by R_{outer} and $R_{\mathrm{ice}} = 1541$ km) overlies an ocean, and where the seabed occurs at radius $R_{\mathrm{bed}} = 1441$ km (all radii being measured from the planet's centre). This is not inconsistent with existing models of Europa (Pappalardo et al., 1998), commensurate with the illustrative purposes of this paper. Assume for this calculation that the sound speed ($c/\mathrm{m\,s^{-1}}$) in this ocean follows the empirical relationship which characterises Earth's oceans in terms of temperature ($T/°\mathrm{C}$) and the hydrostatic pressure ($P_{\mathrm{h}}/\mathrm{Pa}$):

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.0003T^3 + (1.39 - 0.012T)(S - 35) + 1.74 \times 10^{-6} P_{\mathrm{h}}. \tag{1}$$

The simple model of this paper assumes that the salinity (S, in parts per thousand, ppt) is taken to resemble that of Earth's oceans (Khurana et al., 1998; Kivelson et al., 2000), and the ocean temperature is taken to be uniform at $T = 0\,°\mathrm{C}$ unless otherwise stated (Melosh et al., 2004). Let ρ_{w} and ρ_{ice} be the densities of the water and ice respectively (neglecting any variation of these with depth) and let ρ_{E} be the spatially-averaged density of the seabed, mantle and core. Whilst Europa's environment will be more complex than these simple assumptions encapsulate, the model is sufficient to illustrate the effects of this paper. It is not accurate to say that the hydrostatic pressure is $P_{\mathrm{h}} = g(\rho_{\mathrm{w}} z + \rho_{\mathrm{ice}} h_{\mathrm{ice}})$ at some depth z below the base of the ice, where g is the acceleration due to gravity. To do so would be to assume a constant acceleration due to gravity, and to ignore the curvature of Europa's spherical geometry: vertical lines are not parallel on a small planet. Consider the separate components that make up the hydrostatic pressure. We assume an almost zero atmospheric pressure, and ocean depth z as measured positively downwards from the ice/water interface. The assumption of constant densities for the water and ice is maintained throughout this paper.

Whilst on Earth it is usual to ignore the difference in the acceleration due to gravity from the sea surface to the seabed, the effect is much larger on Europa because it is a smaller planetary body, and because the sea depths are believed to be so much greater. The net effect on the gravity will depend on the densities of the material which exist between the point of interest and the centre of the planet. At a location in the water, a distance r_{w} from Europa's centre, the acceleration due to gravity ($g(r_{\mathrm{w}})$) is

$$\begin{aligned} g(r_{\mathrm{w}}) &\approx \frac{G}{r_{\mathrm{w}}^2}\left(\frac{4\pi R_{\mathrm{bed}}^3 \rho_{\mathrm{E}}}{3} + \int_{R_{\mathrm{bed}}}^{r_{\mathrm{w}}} \rho_{\mathrm{w}} 4\pi r^2 \,\mathrm{d}r\right) \\ &= \frac{4\pi G}{3r_{\mathrm{w}}^2}\left(r_{\mathrm{w}}^3 \rho_{\mathrm{w}} + R_{\mathrm{bed}}^3(\rho_{\mathrm{E}} - \rho_{\mathrm{w}})\right), \end{aligned} \tag{2}$$

where $G = 6.67300 \times 10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}}$ is the gravitational constant. Similarly, at a location in the ice, a distance r_{ice} from Europa's centre, the acceleration due to gravity ($g(r_{\mathrm{ice}})$) is

$$g(r_{\mathrm{ice}}) \approx \frac{4\pi G}{3r_{\mathrm{ice}}^2}\left(\left(R_{\mathrm{ice}}^3 - R_{\mathrm{bed}}^3\right)\rho_{\mathrm{w}} + R_{\mathrm{bed}}^3 \rho_{\mathrm{E}} + \left(r_{\mathrm{ice}}^3 - R_{\mathrm{ice}}^3\right)\rho_{\mathrm{ice}}\right). \tag{3}$$

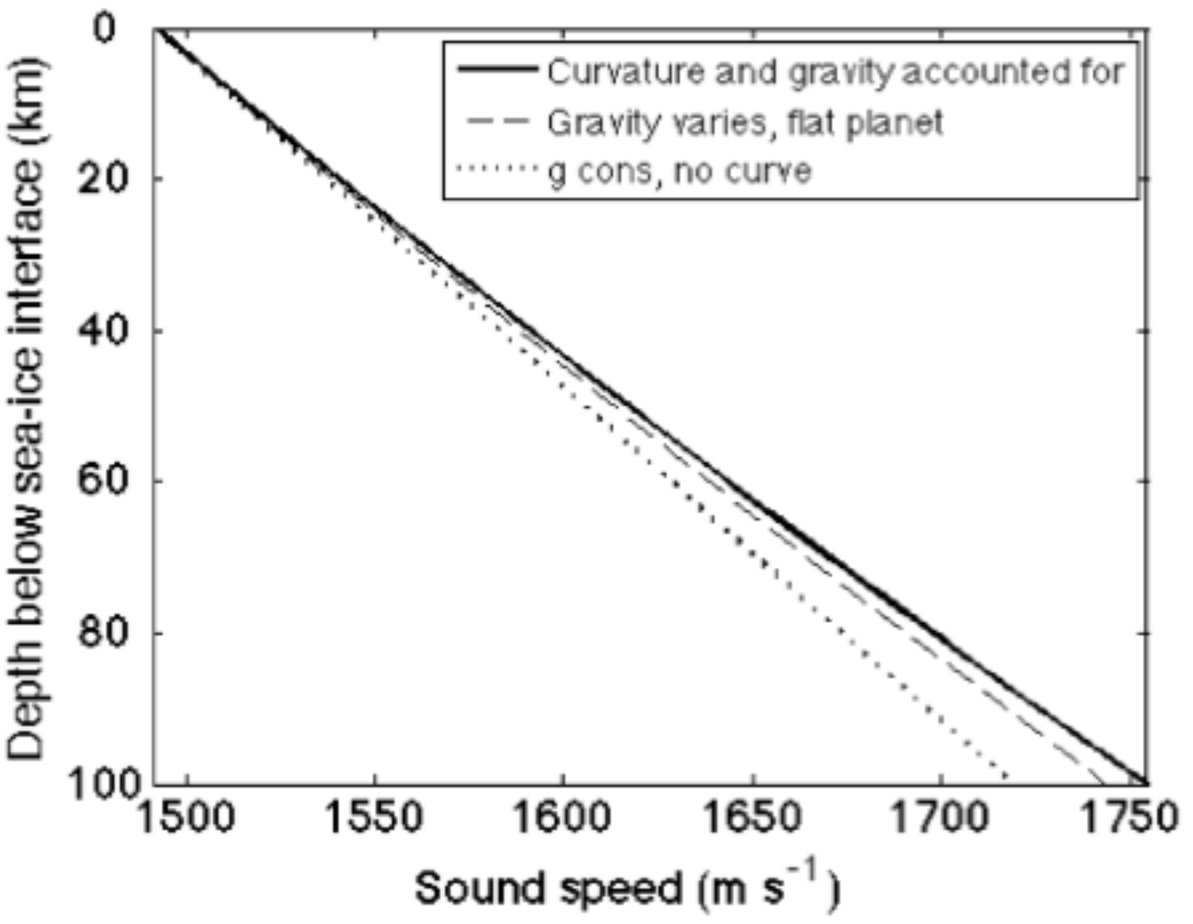


Fig. 1. Calculation of oceanic sound speed as a function of depth beneath the base of the ice sheet, assuming constant densities ($\rho_{\mathrm{w}} = 1000\ \mathrm{kg\,m^{-3}}$, $\rho_{\mathrm{ice}} = 920\ \mathrm{kg\,m^{-3}}$, with $\rho_{\mathrm{E}} = 3550\ \mathrm{kg\,m^{-3}}$ and $S = 35$ ppt, and $T = 0\,°\mathrm{C}$). Solid curve (—) plots c_1, the sound speed calculated including planet curvature and variable gravitational acceleration (i.e., substitution of Eq. (4) into Eq. (1)). For this curve the sound speed gradient is $\mathrm{d}c_1/\mathrm{d}r_{\mathrm{w}} \approx 2.65 \times 10^{-3}\ \mathrm{s^{-1}}$. Dashed curve (– – –) ignores planet curvature but has variable gravitational acceleration. Dotted curve (· · ·) plots c_2, the sound speed calculated ignoring planet curvature and for a gravitational acceleration which is constant at a value of $1.31\ \mathrm{m\,s^{-2}}$ (the value at Europa's surface). For this dotted curve, the sound speed gradient is $\mathrm{d}c_2/\mathrm{d}r_{\mathrm{w}} \approx 2.3 \times 10^{-3}\ \mathrm{s^{-1}}$. Changing the assumed temperature tends to translate all the curves: if the temperature is increased to $T = 4\,°\mathrm{C}$, the sound speeds are all increased by roughly $20\ \mathrm{m\,s^{-1}}$. As a result, the size of errors in Fig. 2 is relatively insensitive to the exact temperature, although in principle the absolute results are sufficiently sensitive to allow inversion of the acoustic data to estimate ocean properties (Leighton et al., 2007).

Assume the parameter values cited in the caption to Fig. 1. From (3), the value of the gravity at the surface of Europa is a little over $1.3\ \mathrm{m\,s^{-2}}$, which is consistent with the values in the literature (Pappalardo et al., 1998), and from (2) is around 10% less than the value at the bottom of the ocean (the gravitational acceleration on the Arctic icepack differs by less than 0.03% from that found at the 1.3 km average depth of the Arctic Ocean seabed).[1] The hydrostatic pressure within Europa's water column approximately equals the sum of the weights of water and ice upon a spherical surface at radius r_{w}, divided by the area of this surface $4\pi r_{\mathrm{w}}^2$:

$$\begin{aligned} P_{\mathrm{h}}(r_{\mathrm{w}}) &= \frac{W_{\mathrm{ice}} + \rho_{\mathrm{w}} \int_{r_{\mathrm{w}}}^{R_{\mathrm{ice}}} 4\pi \tilde{r}_{\mathrm{w}}^2 g(\tilde{r}_{\mathrm{w}})\,\mathrm{d}\tilde{r}_{\mathrm{w}}}{4\pi r_{\mathrm{w}}^2} \\ &= \frac{W_{\mathrm{ice}}}{4\pi r_{\mathrm{w}}^2} + \frac{\rho_{\mathrm{w}} \frac{4\pi G}{3} R_{\mathrm{bed}}^3 (\rho_{\mathrm{E}} - \rho_{\mathrm{w}})(R_{\mathrm{ice}} - r_{\mathrm{w}})}{r_{\mathrm{w}}^2} + \frac{\rho_{\mathrm{w}}^2 \frac{4\pi G (R_{\mathrm{ice}}^4 - r_{\mathrm{w}}^4)}{12}}{r_{\mathrm{w}}^2}, \end{aligned} \tag{4}$$

which is accurate to within 10% at Europa's seabed, although for small planets integration of $\nabla P_{\mathrm{h}} = \rho g$ should be used as follows:

$$\begin{aligned} P_{\mathrm{h}}(r_{\mathrm{w}}) &= \int_{r_{\mathrm{w}}}^{R_{\mathrm{ice}}} \rho_{\mathrm{w}} g(\tilde{r}_{\mathrm{w}})\,\mathrm{d}\tilde{r}_{\mathrm{w}} + \int_{R_{\mathrm{ice}}}^{R_{\mathrm{outer}}} \rho_{\mathrm{ice}} g(\tilde{r}_{\mathrm{ice}})\,\mathrm{d}\tilde{r}_{\mathrm{ice}} \\ &= \frac{4\pi G \rho_{\mathrm{ice}}}{3}\Big(\left(R_{\mathrm{ice}}^{-1} - R_{\mathrm{outer}}^{-1}\right)\left(\left(R_{\mathrm{ice}}^3 - R_{\mathrm{bed}}^3\right)\rho_{\mathrm{w}} + R_{\mathrm{bed}}^3 \rho_{\mathrm{E}} - R_{\mathrm{ice}}^3 \rho_{\mathrm{ice}}\right) \\ &\quad + \rho_{\mathrm{ice}}\left(R_{\mathrm{outer}}^2 - R_{\mathrm{ice}}^2\right)/2\Big) \\ &\quad + \frac{4\pi G \rho_{\mathrm{w}}}{3}\left(\rho_{\mathrm{w}}\left(R_{\mathrm{ice}}^2 - r_{\mathrm{w}}^2\right)/2 + R_{\mathrm{bed}}^3(\rho_{\mathrm{E}} - \rho_{\mathrm{w}})\left(r_{\mathrm{w}}^{-1} - R_{\mathrm{ice}}^{-1}\right)\right) \end{aligned} \tag{5}$$

which now remains bounded as $r_{\mathrm{w}} \to R_{\mathrm{bed}} \to 0$, where $g(r_{\mathrm{w}})$ and $g(r_{\mathrm{ice}})$ are given by Eqs. (2) and (3) respectively, and where the weight of the ice sheet

---

[1] In this paper, the number of significant figures quoted with numerical values does not reflect confidence in the accuracy of those values. Rather, it represents the precision required to distinguish estimates obtained from the following analysis, from those which are given for comparison following 'back-of-the-envelope' calculations.

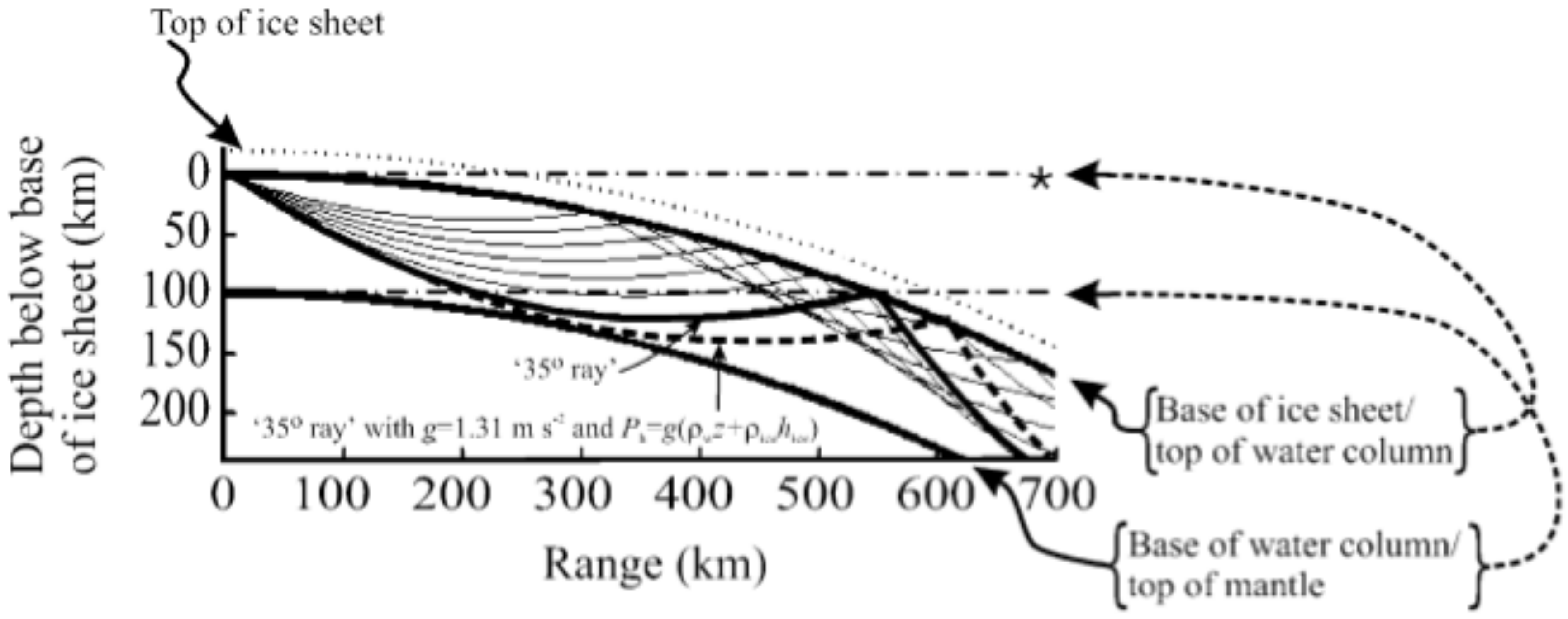


Fig. 2. Predicted ray paths within the curved ocean (the location of the ocean boundaries if curvature is ignored are also shown), calculated when Eq. (4) is used in Eq. (1) for the conditions indicated in the caption to Fig. 1. The deepest of the selection of rays calculated in this way had a launch angle of 35° below the horizontal, and is plotted with a thick solid line, and labelled '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.

in (4) is $W_{\text{ice}} = \rho_{\text{ice}} \int_{R_{\text{ice}}}^{R_{\text{outer}}} 4\pi \tilde{r}_{\text{ice}}^2 g(\tilde{r}_{\text{ice}})\, d\tilde{r}_{\text{ice}}$. Substitution of (5) into (1) allows the variation with depth of the sound speed in the ocean to be calculated. The full calculations using (4) in (1) are compared in Fig. 1 with the more approximate forms obtained for the sound speed profile. Fig. 1 implies that the sound speed will increase with depth (and therefore acoustic propagation in the ocean will be upwardly refracting; Leighton et al., 2006). This increase is approximately linear with depth [to within 3%, as confirmed by differentiation of (1) (with (5) used for P_h) with respect to z]. Such a linear approximation would be physically equivalent to ignoring the variation of gravity with depth, and the effect of the curvature of the planet. The influence of these two effects will now be estimated.

3. Results

The variation in gravitational acceleration and the curvature of Europa were incorporated into the computational model for ray propagation in the ocean (with properties assumed as in caption of Fig. 1). Neither potential deviations from sphericity nor horizontal gradients have been incorporated, though such effects have been shown to have a profound effect on Earth (Munk et al., 1988). The interface between water and ice was modelled as perfectly reflecting.

Fig. 2 shows the paths of a series of rays, calculated with the incorporation both of variable g and where the hydrostatic pressure is calculated using conic, rather than rectilinear, sections. The top and bottom of the ice sheet, and the top of the mantle, are shown. Also shown are the locations that these physical boundaries would take if the curvature of the planet were ignored, indicating the large errors that would occur in calculations of propagations over several hundred km (distances which are relevant for, say, the remote detection of meteor impacts or other large events). The changes to the sound speed profile shown in Fig. 1 will affect all through-water ray paths/travel times over a sufficient distance, but for clarity a single ray is chosen to demonstrate this in Fig. 2. The deepest of the series of plotted rays is labelled (the '35° ray'). The figure also shows its path were it to be calculated with the assumption that g is constant at 1.31 $\text{m}\,\text{s}^{-2}$ (the value for gravity at the surface), and were hydrostatic pressure to be calculated using rectilinear sections (i.e., $P_h = g(\rho_w z + \rho_{\text{ice}} h_{\text{ice}})$). The discrepancy is considerable, with, for example, a >50 km overestimate in the range at which the ray that was launched at 35° below the horizontal first reflects off the ice.[2] Such errors increase with range, and are important if, for example, acoustic propagation right around the planet is modelled (for example, to diagnose the oceanic conditions) (Leighton et al., 2007). Note that if the original ray chosen for this study had been slightly deeper, then the neglect of these effects would have caused reflections from the seabed: when the character of the propagation is changed qualitatively in this way, the effect can be more significant than the percentage changes implied above. The circumpropagation simulations of oceans in Europa undertaken by Leighton et al. (2007) show the importance of the correct modelling of the qualitative ray paths when quantitatively predicting acoustic travel times: a small change in the assumed ocean temperature or depth can lead to a much greater proportional change in travel time if it alters the number of reflections at the water/ice interface required for a specific return.

4. Conclusions

On a small planet, assumptions which are common in ocean acoustic models for Earth may no longer hold. The assumption that the acceleration due to gravity is independent of depth, and the assumption that the hydrostatic pressure can be calculated using rectilinear sections, were shown on a planet resembling Europa to lead to significant errors. Whilst these effects may be negligible on other planets (where the ocean makes up a smaller proportion of the radius), their effects should be quantitatively assessed using the methods of this paper so that any neglect of such effects can be justified or shown to be questionable. This procedure is also applicable to the modelling of non-acoustic phenomena such as heat convection, mass flux, and glacial/tectonic interaction (Lee et al., 2003; Showman and Han, 2005). Such justification for neglecting relevant physics should not be based on misleading comparisons between the systematic sound speed discrepancies described in this paper, and the current uncertainties in the values of other parameters (e.g., ocean temperature and salinity variations) whose physics is correctly incorporated into the models but whose values are estimated with uncertainty which may be reduced as further data becomes available. This is because acoustic inversions based on a model which contains significant systematic errors in the physics can produce misleading answers. The formulations outlined in this paper provide a simple basis for generating a more accurate model.

References

Bouchy, F., Bazot, M., Santos, N.C., Vauclair, S., Sosnowska, D., 2005. Asteroseismology of the planet-hosting star μ Arae. I. The acoustic spectrum. Astron. Astrophys. 440, 609–614.

Crawford, G.D., Stevenson, D.J., 1988. Gas driven water volcanism in the resurfacing of Europa. Icarus 73, 66–79.

Delory, G.T., Luhmann, J.G., Curtis, D.W., Friedman, L.D., Primbsch, J.H., Mozer, F.S., 1998. Development of an audio microphone for the Mars Surveyor 98 Lander. In: Proceedings of the First International Conference on Mars Polar Science and Exploration, Lunar and Planetary Institute Contributions No. 953, p. 6.

Elsworth, Y., Howe, R., Isaak, G.R., McLeod, C.P., New, R., 1990. Variation of low-order acoustic solar oscillations over the solar cycle. Nature 345, 322–324.

Fulchignoni, M., Ferri, F., Angrilli, F., Ball, A.J., Bar-Nun, A., Barucci1, M.A., Bettanini, C., Bianchini, G., Borucki, W., Colombatti, G., Coradini, M.,

---

[2] If one were neglecting ice pack curvature and calculating the distance to intersect the base of the ice sheet at * in Fig. 2, the error would be $2(c_{1,\text{i}}/(\text{d}c_1/\text{d}r_\text{w}) - c_{2,\text{i}}/(\text{d}c_2/\text{d}r_\text{w}))\sin\theta \approx 2(1750/(2.65\times10^{-3}) - 1720/(2.3\times10^{-3}))\sin 35 \approx 100$ km, where $c_{1,\text{i}}$ and $c_{2,\text{i}}$ are the sound speeds where each of the respective rays attains horizontal trajectory (Leighton, 1998).

Coustenis, A., Debei, S., Falkner, P., Fanti, G., Flamini, E., Gaborit, V., Grard, R., Hamelin, M., Harri, A.M., Hathi, B., Jernej, I., Leese, M.R., Lehto, A., Lion Stoppato, P.F., López-Moreno, J.J., Mäkinen, T., McDonnell, J.A.M., McKay, C.P., Molina-Cuberos, G., Neubauer, F.M., Pirronello, V., Rodrigo, R., Saggin, B., Schwingenschuh, K., Seiff, A., Simões, F., Svedhem, H., Tokano, T., Towner, M.C., Trautner, R., Withers, P., Zarnecki, J.C., 2005a. In situ measurements of the physical characteristics of Titan's environment. Nature 438, 785–791.

Fulchignoni, M., Ferri, F., Colombatti, G., Zarnecki, J.C., Harri, H.M., Hamelin, M., Lopez-Moreno, J.J., Schwingenshuh, K., Angrilli, F., and HASI Team, 2005b. HASI Experiment to Titan. Bull. Am. Astron. Soc. 37, 621. Abstract.

Fulchignoni, M., Ferri, F., and HASI Team, 2006. Recent results on Titan from the HASI instrument. Geophys. Res. Abstr. 8, 10178. Abstract.

Greenberg, R., 2002. Tides and the biosphere of Europa. Am. Sci. 90, 48–55.

Gupta, M.R., Sarkar, S., Ghosh, S., Debnath, M., Khan, M., 2001. Effect of nonadiabaticity of dust charge variation on dust acoustic waves: Generation of dust acoustic shock waves. Phys. Rev. E 63, 046406-1–046406-9.

Hoppa, G., Greenberg, R., Tufts, B.R., Geissler, P., Phillips, C., Milazzo, M., 2000. Distribution of strike-slip faults on Europa. J. Geophys. Res. 105 (22), 617–628.

Khurana, K.K., Kivelson, M.G., Stevenson, D.J., Schubert, G., Russell, C.T., Walker, R.T., Polanskey, C., 1998. Induced magnetic fields as evidence for sub-surface oceans in Europa and Callisto. Nature 395, 777–780.

Kivelson, M.G., Khurna, K.K., Russell, C.T., Volwerk, M., Walker, R.J., Zimmer, C., 2000. Galileo magnetometer measurements: A stronger case for subsurface ocean at Europa. Science 289, 1340–1343.

Kovach, R.L., Chyba, C.F., 2001. Seismic detectability of a subsurface ocean on Europa. Icarus 150, 279–287.

Ksanfomality, L., Goroschkova, N.V., Khondryev, V., 1983a. Wind velocity near the surface of Venus from acoustic measurements. Cosmic Res. 21, 161–167.

Ksanfomality, L.V., Scarf, E.L., Taylor, F., 1983b. The electrical activity of the atmosphere of Venus. In: Hunten, D.M. (Ed.), Venus. Univ. of Arizona Press, Tucson, AZ.

Lebreton, J.P., Witasse, O., Sollazzo, C., Blancquaert, T., Couzin, P., Schipper, A.-M., Jones, J.B., Matson, D.L., Gurvits, L.I., Atkinson, D.H., Kazeminejad, B., Pérez-Ayúcar, M., 2005. An overview of the descent and landing of the Huygens probe on Titan. Nature 438, 758–764.

Lee, U., 1993. Acoustic oscillations of Jupiter. Astrophys. J. 405, 359–374.

Lee, S., Zanolin, M., Thode, A.M., Pappalardo, R.T., Makris, N.C., 2003. Probing Europa's interior with natural sound sources. Icarus 165, 144–167.

Lee, S., Pappalardo, R.T., Makris, N.C., 2005. Mechanics of tidally driven fractures in Europa's ice shell. Icarus 177, 367–379.

Leighton, T.G., 1998. Fundamentals of underwater acoustics and ultrasound. In: Fahy, F.J., Walker, J.G. (Eds.), Noise and Vibration. E&F Spon, London, p. 390, chap. 7.

Leighton, T.G., 2004. From seas to surgeries, from babbling brooks to baby scans: The acoustics of gas bubbles in liquids'. Int. J. Mod. Phys. B 18 (25), 3267–3314.

Leighton, T.G., 2007. The use of acoustics in space exploration. ISVR Technical Report 314, University of Southampton.

Leighton, T.G., White, P.R., 2004. The sound of Titan: A role for acoustics in space exploration. Acoust. Bull. 29, 16–23.

Leighton, T.G., White, P.R., Finfer, D.C., 2005. The sounds of seas in space. In: Papadakis, J.S., Bjorno, L. (Eds.), Proceedings of the International Conference on Underwater Acoustic Measurements, Technologies and Results, pp. 833–840.

Leighton, T.G., White, P.R., Finfer, D.C., Grover, E.J., 2006. The sounds of seas in space: The 'waterfalls' of Titan and the ice seas of Europa. Proc. Inst. Acoust. 28 (1), 75–97.

Leighton, T.G., Finfer, D.C., White, P.R., 2007. Ocean acoustic circumpropagation in the ice seas of Europa. ISVR Technical Report 319, University of Southampton.

Makris, N.C., 2001. Probing for an ocean on Jupiter's Moon Europa with natural sound sources. Echoes 11 (3), 1–3.

Makris, N.C., Lee, S., Thode, A., Wilson, J.D., Zanolin, M., Pappalardo, R.T., 2001. Probing Europa's interior structure with natural ambient noise. In: American Geophysical Union, Fall Meeting 2001. Abstract #P22B-0552.

McDonald, B.E., Collins, M.D., Kuperman, W.A., Heaney, K.D., 1994. Comparison of data and model predictions for Heard Island acoustic transmissions. J. Acoust. Soc. Am. 96, 2357–2370.

Melosh, H.J., Ekholm, A.G., Showman, A.P., Lorenz, R.D., 2004. The temperature of Europa's subsurface water ocean. Icarus 168, 498–502.

Merlino, R.L., 1997. Current-driven dust ion acoustic instability in a collisional dusty plasma. IEEE Trans. Plasma Sci. 25, 60–65.

Mikhalevsky, P.N., Gavrilov, A.N., 2001. Acoustic thermometry in the Arctic Ocean. Polar Res. 20, 185–192.

Muir, H., 2007. Sounds in space. New Sci. 195 (2616), 28–32.

Munk, W.H., O'Reilly, W.C., Reid, J.L., 1988. Australia-Bermuda sound transmission experiment (1960) revisited. J. Phys. Oceanogr. 18, 1876–1898.

Nimmo, F., Schenk, P., 2006. Normal faulting on Europa: Implications for ice shell properties. J. Struct. Geol. 28, 2194–2203.

Panning, M., Lekic, V., Manga, M., Cammarano, F., Romanowicz, B., 2006. Long-period seismology on Europa. 2. Predicted seismic response. J. Geophys. Res. 111, doi:10.1029/2006JE002712. E12008.

Pappalardo, R.T., Head, J.W., Greeley, R., Sullivan, R.J., Pilcher, C., Schubert, G., Moore, W.B., Carr, M.H., Moore, J.M., Belton, M.J.S., Goldsby, D.L., 1998. Geological evidence for solid-state convection in Europa's ice shell. Nature 391, 365–368.

Petculescu, A., Lueptow, R.M., 2007. Atmospheric acoustics of Titan, Mars, Venus, and Earth. Icarus 186, 413–419.

Pieper, J.B., Goree, J., 1996. Dispersion of plasma dust acoustic waves in the strong-coupling regime. Phys. Rev. Lett. 77, 3137–3140.

Rammacher, W., Ulmschneider, P., 1992. Acoustic waves in the solar atmosphere. IX. Three minute pulsations driven by shock overtaking. Astron. Astrophys. 253, 586–600.

Rosenberg, M., Kalman, G., 1997. Dust acoustic waves in strongly coupled dusty plasmas. Phys. Rev. E 56, 7166–7173.

Schenk, P.M., McKinnon, W.B., 1989. Fault offsets and lateral crustal movement on Europa: Evidence for a mobile ice shell. Icarus 79, 75–100.

Showman, A.P., Han, L., 2005. Effects of plasticity on convection in an ice shell: Implications for Europa. Icarus 177, 425–437.

Shukla, P.K., 2000. Dust acoustic wave in a thermal dusty plasma. Phys. Rev. E 61, 7249–7251.

Stofan, E.R., Elachi, C., Lunine, J.I., Lorenz, R.D., Stiles, B., Mitchell, K.L., Ostro, S., Soderblom, L., Wood, C., Zebker, H., Wall, S., Janssen, M., Kirk, R., Lopes, R., Paganelli, F., Radebaugh, J., Wye, L., Anderson, Y., Allison, M., Boehmer, R., Callahan, P., Encrenaz, P., Flamini, E., Francescetti, G., Gim, Y., Hamilton, G., Hensley, S., Johnson, W.T.K., Kelleher, K., Muhleman, D., Paillou, P., Picardi, G., Posa, F., Roth, L., Seu, R., Shaffer, S., Vetrella, S., West, R., 2007. The lakes of Titan. Nature 445, 61–64.

Tokano, T., McKay, C.P., Neubauer, F.M., Atreya, S.K., Ferri, F., Fulchignoni, M., Niemann, H.B., 2006. Methane drizzle on Titan. Nature 442, 432–435.

Verheest, F., 1993. Are weak dust-acoustic double layers adequately described by modified Korteweg–de Vries equations? Phys. Scripta 47, 274–277.

Wage, K.E., Baggeroer, A.B., Preisig, J.C., 2003. Modal analysis of broadband acoustic receptions at 3515-km range in the North Pacific using short-time Fourier techniques. J. Acoust. Soc. Am. 113, 801–817.

Zarnecki, J.C., Leese, M.R., Hathi, B., Ball, A.J., Hagermann, A., Towner, M.C., Lorenz, R.D., McDonnell, J.A.M., Green, S.F., Patel, M.R., Ringrose, T.J., Rosenberg, P.D., Atkinson, K.R., Paton, M.D., Banaszkiewicz, M., Clark, B.C., Ferri, F., Fulchignoni, M., Ghafoor, N.A.L., Kargl, G., Svedhem, H., Delderfield, J., Grande, M., Parker, D.J., Challenor, P.G., Geake, J.E., 2005. A soft solid surface on Titan as revealed by the Huygens Surface Science Package. Nature 438, 792–795.