SONAR EQUATIONS FOR PLANETS AND MOONS

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A set of equations to describe the performance of sonar systems, collectively known as the "sonar equations", was developed during and after the Second World War. These equations assumed that both the sonar equipment and the object to be detected (usually a submarine) would be submerged in one of Earth's seas or oceans, and the efficacy of the sonar equations is long established for this situation. Looking ahead into the 21st century, the proposed use of sonar in the exotic oceans of Europa, Ganymede or Titan demands a fresh look at the 50-year-old sonar equations to assess their suitability for this new purpose. Examples are given for Europa's icy ocean, one of Titan's hydrocarbon lakes, and Jupiter's dense gaseous atmosphere.

1. Introduction

The sinking of RMS *Titanic* in 1912 followed by the outbreak of the First World War in 1914 precipitated an unprecedented period of transatlantic research focused on the detection and localization of underwater objects. Little further progress was made between the wars until research resumed again during and after the Second World War [1]. The need to quantify the performance of these systems was then met by a set of equations, known as the "sonar equations", relating the signal to noise ratio and probabilities of detection and false alarm to basic system properties such as background noise level and transmitted sound power. These equations assumed, not unreasonably at the time, that both the sonar equipment and the object to be detected (the "target") would be submerged in one of Earth's seas or oceans. The impedance of seawater was therefore treated as a constant, independent of the precise location [2].

The essence of these sonar equations is summarized in Sec. 2, comparing traditional equations from Urick's book [2, 3] with those from a new international standard [4]. In contrast to the traditional sonar equations, the ISO standard makes no *a priori* assumption requiring the impedance of the medium to be uniform. The ISO sonar equations are therefore applicable in any fluid medium, regardless of impedance, including extra-terrestrial seas, oceans and atmospheres, as illustrated by the examples of Sec. 3.

2. The sonar equations

2.1 Active and passive sonar

Active sonar uses the principle of echolocation. In other words, a pulse of sound (or ultrasound) is transmitted by the sonar system, reflected from a submerged target, and the resulting echoes are sensed by the sonar receiver. The time delay between transmission and reception indicates the distance to the target, while phase differences between receiver elements provide bearing information.

Unlike active sonar, passive sonar equipment does not transmit sound. Instead it listens for sounds radiated by the target. Target bearing is estimated from the phase difference between receiver elements, in the same way as for active sonar. The target distance needs to be estimated by combining bearing estimates from different receivers, or from the rate of change of bearing on a single receiver.

The sonar equation takes a different form for passive and active sonar.

2.2 Passive sonar equation applicable to Earth's oceans

Sonar equations in widespread use are described by Urick [3]. Urick's passive sonar equation is

(1)
$$\mathrm{SE} = \mathrm{SL} - \mathrm{TL} - \mathrm{NL} + \mathrm{DI} - \mathrm{DT},$$

where SL, TL, NL, DI and DT are known as the source level, transmission loss, noise level, directivity index, and detection threshold, respectively. The left hand side (SE) is the signal excess (Urick 1983 [3], p.388). These levels and level differences are all logarithms of ratios of quantities proportional to sound intensity, and are traditionally expressed in decibels (dB). For example, TL is the transfer function from source to receiver, while the noise level is

(2)
$$\mathrm{NL} = 10 \log_{10} \frac{I_{\mathrm{N},f}}{I_0 / f_0} \mathrm{dB},$$

where $I_{\mathrm{N},f} = (\rho c)^{-1} \mathrm{d}\, p_\mathrm{N}^{\,2} / \mathrm{d}f$, ρc is the characteristic impedance of the fluid medium at the sonar receiver position, and $\mathrm{d}p_\mathrm{N}^2/\mathrm{d}f$ is the spectral density of the mean-square noise sound pressure. Here and throughout this paper, where a sonar equation term is expressed as a level in decibels, the argument of the logarithm is a ratio of a power quantity (such as mean-square sound pressure) to the reference value of that power quantity.

The denominator of Eq. (2), I_0/f_0, is the reference value of intensity spectral density, equal to the ratio of the reference intensity I_0 to the reference frequency f_0, where f_0 = 1 Hz [5]. The modern international standard reference value of sound intensity is I_0 = 1 pW/m^2, (1 pW = one picowatt = 10^{-12} W). This value of I_0 has been the international standard since 1994 [6], and the ANSI (American National Standards Institute) standard since 1960 [7], but for historical reasons is rarely (if ever) used in underwater acoustics. Instead it is traditional to use a reference intensity of the form [2, 3, 8]

(3)
$$I_0 = p_0^{\,2} / (\rho_0 c_0),$$

where p_0 and $\rho_0 c_0$ are reference values of sound pressure and impedance, respectively. The denominator and numerator of Eq. (3) are considered in turn below.

The absence of a standard reference value for the impedance of water makes the denominator of Eq. (3) necessarily imprecise. A popular value for $\rho_0 c_0$ is 1.5 MPa s/m [3, 8], which is high for fresh water and low for seawater, making it a reasonable compromise value in situations for which accuracy is not paramount. A standard value in use prior to 1960 [9] was 1.53507 MPa s/m. A spread of likely values suggested by the ANSI standard S1.1-1960 [7] is between 1.4183 MPa s/m (cold fresh water) and 1.5698 MPa s/m (warm seawater). While this spread might seem a small difference compared with uncertainties resulting from measurement error, for a *definition* such an ambiguity is both unnecessary and undesirable.

The international standard reference value of sound pressure for use in water is p_0 = 1 μPa [6, 10]. Substituting this value with $\rho_0 c_0$ = 1.5 MPa s/m in Eq. (3) gives $I_0 \approx 6.7\times10^{-7}$ pW/m^2, which is widely cited [3, 8]. Adopting the representative spread of water impedance from ANSI standard S1.1-1960 gives an associated uncertainty in I_0 of 6.37×10^{-7} pW/m^2 to 7.05×10^{-7} pW/m^2.

The sonar equation in the form of Eq. (1) is still in use in the 21st century, still with the ambiguity implied by Urick's choice of reference intensity [8, 11]. Given that a sonar might be calibrated in either fresh water or seawater (or both), and given the absence of consensus in either situation of what value of impedance to use in Eq. (3) (possibilities include for example the impedance of fresh water, the impedance of seawater, and Urick's nominal value), Horton [12] argued in 1959 that this uncertainty on its own can lead to undesirable calibration errors of ca. 0.5 dB. In order to avoid such errors he advocated the use of a constant value of I_0 equal to 10 kW/m^2 (i.e., 1 W/cm^2, the unit of intensity in the centimetre-gram-second system), but Horton's warning went unheeded for half a century. For as long as Urick's conventions continue to be followed, any potential for improvement to this 0.5 dB limit is unattainable despite unprecedented advances in measurement technology during the intervening half century, and will remain illusory irrespective of future advances.

2.3 Passive sonar equation applicable to planetary exploration

In 2012, Sub-Committee 3 (Underwater Acoustics) of Technical Committee 43 (Acoustics) of the International Organization for Standardization (ISO) established a working group with the purpose of developing an international terminology standard for underwater acoustics. That working group produced a draft international standard (ISO 18405 [4]) in 2014 (expected to be published in April 2015), and plans to upgrade this draft to a full International Standard in the last quarter of 2015. The draft international standard adopts the symbols L_{SL} for source level, N_{PL} for propagation loss, L_{NL} for sonar noise level, ΔL_{PG} for processing gain and ΔL_{DT} for detection threshold. In this notation, the passive sonar equation, relating the signal excess ΔL_{SE} to the other terms, is

(4) $$\Delta L_{\mathrm{SE}} = L_{\mathrm{SL}} - N_{\mathrm{PL}} - L_{\mathrm{NL}} + \Delta L_{\mathrm{PG}} - \Delta L_{\mathrm{DT}}.$$

While Eq. (4) has the same form as Urick's sonar equation, the similarity is deceptive, as there are differences in the definitions of individual terms that can lead to large differences in the magnitudes of some of them. For example, Urick defines noise level (NL) as the level of a spectral density, Eq. (2), whereas in the ISO sonar equation, L_{NL} is the total noise level in a specified frequency band:

(5) $$L_{\mathrm{NL}} = 10\log_{10}\frac{p_{\mathrm{N}}^2}{p_0^2}\,\mathrm{dB}.$$

There are two important differences between the numerators of Eqs. (2) ($I_{\mathrm{N},f}$), and (5) (p_{N}^2). The first difference is that one ($I_{\mathrm{N},f}$) is a spectral density and the other not, and in the following, this difference is deliberately hidden by arbitrarily selecting a frequency band of 1 Hz. The second difference, which we choose to focus on, is the division by impedance in Urick's sonar equation terms to convert to an equivalent sound intensity before converting to a level in decibels. The result of this second difference is a systematic difference between SL, TL, NL on the one hand and their ISO counterparts L_{SL}, N_{PL}, L_{NL} on the other, that depends on the medium's characteristic impedance either at source or receiver or both. For example, L_{NL} and NL are related via [13]

(6) $$L_{\mathrm{NL}} = \mathrm{NL} + 10\log_{10}\left[(\rho_{\mathrm{r}} c_{\mathrm{r}})/(\rho_0 c_0)\right]\mathrm{dB},$$

with similar equations holding for L_{SL} and N_{PL}.

The correction terms (L_{NL} – NL, L_{SL} – SL and N_{PL} – TL) are all of the form $10\log_{10}$(impedance ratio) dB, although the specific form of the impedance ratio is different for each. For traditional applications these corrections are small in magnitude because the impedance of seawater on Earth is approximately uniform and departs little from Urick's choice of $\rho_0 c_0$ = 1.5 MPa s/m. Recalling that missions that deploy sonar sensors are already being conceived for Titan's lakes [14], Europa's oceans [15, 16, 17] and Jupiter's atmosphere [18, 19], it is worth noting that in exotic conditions such as exist on these planets and moons, the correction terms are not necessarily small [20]. For this reason, and because the definitions of its individual terms do not rely on an arbitrary choice of reference impedance, Eq. (4) is suitable for application in planetary exploration, whereas Eq. (1) is not.

2.4 Active sonar equation

Urick's active sonar equation, in the form quoted by Jensen et al. (2011) [8], is

$$\mathrm{SE} = \mathrm{SL} - \mathrm{TL}_1 + \mathrm{TS} - \mathrm{TL}_2 - \mathrm{NL} + \mathrm{DI} - \mathrm{DT}, \tag{7}$$

where TL_1 is the "transmission loss" from sonar transmitter to target, TL_2 is the equivalent quantity for the return path from target to sonar receiver, and TS is the target strength. The main difference between this active sonar equation and Urick's passive sonar equation is that here TL is replaced by TL_1 – TS + TL_2, which is the transfer function from source to receiver for active sonar.

The corresponding equation from ISO 18405 [4] is

$$\Delta L_{\mathrm{SE}} = L_{\mathrm{SL}} - N_{\mathrm{PL,Tx}} + N_{\mathrm{TSeq}} - N_{\mathrm{PL,Rx}} - L_{\mathrm{NL}} + \Delta L_{\mathrm{PG}} - \Delta L_{\mathrm{DT}}. \tag{8}$$

where the propagation loss from sonar transmitter to target, $N_{\mathrm{PL,Tx}}$, the equivalent quantity for the return path from target to sonar receiver, $N_{\mathrm{PL,Rx}}$, and the equivalent target strength, N_{TSeq}, are closely related to TL_1, TL_2 and TS [8].

3. Extra-terrestrial examples

3.1 Titan

In 2001, Garry and Towner [15] stated that "The Huygens probe *en route* to Titan carries a 15 kHz non-beam forming sonar…that delivers a signal of ~80 dB (ref 20 µPa) in the laboratory. In the event of landing in a sufficiently deep body of liquid, the sensor works as a bathometer, inferring the 'sea' depth from the echo's delay".

It was only after the actual splashdown that the presence of hydrocarbon lakes was confirmed, a notable one being *Ligeia Mare*, a several-hundred-kilometre wide lake near Titan's north pole. In 2013, Arvelo and Lorenz [14] described a possible future Titan Mare Explorer (TiME) mission, which would splashdown a capsule to operate for three months. Among TiME's scientific goals is the determination of the depth of *Ligeia*, using an acoustic depth sounder. Specifically, Arvelo and Lorenz conducted a theoretical study of the likely performance of this depth sounder. For the noise level term they used a prediction from Leighton et al. (2005) [21] that the "power spectral density for bubble entrainment noise" was expected to be about 10 dB higher on Titan than on Earth for the frequency of interest, from which Arvelo and Lorenz estimated the wind-driven noise level to be "NLo = 40 dB//1 µPa^2/Hz ".

Not one of the above-mentioned publications mention, in association with the signal or noise level in decibels, either the reference value of sound intensity or the impedance used to calculate that reference intensity, which means that the reader is left to guess. Our purpose in making this point is not to criticize any of the authors but to point out the complacency of conventional practice in underwater acoustics, and the consequences of this complacency if transferred to planetary exploration. If Ref. [14] adheres to Urick's definition of noise level as stated in Eq. (2), for example, does this imply the impedance of seawater is being assumed for the reference intensity or some other (unspecified) nominal characteristic acoustic impedance of the nitrogen atmosphere or the liquid of *Ligeia*? In the latter case, depending on the chosen value for impedance, the reference intensity might be anything from 6.5×10^{-7} pW/m^2 (if the impedance of seawater is used to define the reference intensity) to 14.9×10^{-7} pW/m^2 (using the impedance of methane). Without a clear specification of the reference intensity, any statement about noise level on Titan incorporates an inherent factor of 2.4 uncertainty in the intended value of $I_{\mathrm{N},f}$ in Eq. (2), corresponding to 3.8 dB uncertainty in the level. Clearly if such calculations are being undertaken, the issues highlighted in this paper need to be addressed during the planning of any future Titan mission [22]. The ambiguity can be removed by defining sonar equation terms in terms of ratios of mean square sound pressures instead of equivalent intensities [20].

3.2 Europa and the icy moons

Liquid water oceans are thought to exist beneath the surfaces of icy moons such as Europa [23] and Ganymede [24] , with a combination of radiation, geothermal action, and the passage through massive planetary gravitational fields providing the heat necessary to prevent the water from freezing. The evidence of rich chemistry on Europa [25, 26], and the knowledge that Earth supports some deep-ocean life that is not reliant on solar radiation, has stimulated planning for missions to these bodies. Given that acoustics provides by far the most useful radiation for exploring Earth's oceans, it would be inconceivable not to equip such missions with sonar.

Sonar modelling has been done for both the ice and the ocean on Europa [16, 17, 27, 28, 29, 30]. However, despite the apparent similarity to Earth's Arctic Ocean, the application of the familiar techniques developed for that environment would lead to errors in planning and interpreting sonar missions on Europa. In Earth's oceans it is common to equate the hydrostatic pressure (p_{h}, an extremely important parameter in ocean acoustics through its effect on the sound speed) to the product ρgh. Leighton et al. (2008) [17] showed that this approximation does not hold on Europa and other icy moons. Based on water sound speeds of 1500 and 1770 m/s for a receiver at the base of the ice pack and a transmitter on the seabed [29], calculations of the propagation loss would incur an uncertainty of approximately $10\log_{10}(1770/1500)$ dB ~ 0.7 dB discrepancy if Urick's convention (Eq. (7)) were used, a discrepancy that Horton's approach would eliminate. Higher pressure, and therefore a larger discrepancy associated with a larger impedance contrast, is expected on Ganymede.

3.3 Dense atmospheres: Venus and the gas giants

The fortuitous collision of Comet Shoemaker-Levy 9 with Jupiter allowed some authors to consider the propagation of pressure waves in the atmosphere [31, 32, 33], facilitated by data from Voyager mission [34]. Leighton (2009) [18] considered the fluid-structure interactions on man-made probes introduced into Jupiter's atmosphere. He calculated conditions for two locations of possible interest for future probes to Jupiter. The first of these was the '1 bar' altitude, at an equatorial radius of 71,492 km from Jupiter's centre, where p_{h} =1 bar (10^5 Pa), $\rho = 0.1$ kg m^{-3}, and $T \sim 165$ K. The second was the estimated 'maximum operational penetration depth' of some future very robust probe, which he estimated by extrapolating from current terrestrial seismic sensors could withstand a maximum static pressure of $p_{\mathrm{h}} = 0.9$ GPa, calculated to occur 69,600 km from Jupiter's centre, where $T \sim 2000$ K and $\rho \sim 50$ kg m^{-3}. An acoustic transmitter, dropped from the dirigible at the '1 bar' altitude, would fall about 1900 km before reaching this limit of operation. Leighton [18] compared the fluid loading on a range of structures at these two altitudes, and considered how the change in the density around them would affect their natural and resonance frequencies, almost halving the natural frequencies of some components, notably pipes, as the structure descended.

On Venus the atmospheric density at the surface of the planet is not dissimilar to that at the 'maximum operational penetration depth' position discussed for Jupiter (above). On Venus's floor the atmosphere is about 50 times more dense (~65 kg/m^3) than Earth's (~1.29 kg/m^3) and its speed of sound is greater (~410 m/s on Venus and ~340 m/s on the Earth). The increased density and sound speed of the ground-level atmosphere of Venus give it a characteristic acoustic impedance of about 27 kPa s/m, which is 60 times larger than that found in Earth's atmosphere, of 0.44 kPa s/m. This factor 60 leads to an ambiguity of about 18 dB (i.e., $10\log_{10}60$ dB) in the interpretation of levels expressed using the traditional conventions of underwater acoustics and sonar [2, 3, 8], as exemplified by Eq. (6).

Fluid loading and coupling are just two of the fluid-structure interactions of acoustical relevance, and these calculations assume that the properties of the structure itself remain unaffected by the extreme change in conditions as it descends. An additional concern in these dense atmospheres under high pressure (see Figure 1), of vital importance to clarity of communication, is the blurred distinction between gases and liquids, leading to uncertainty about whether one should use 20 μPa or 1 μPa as a reference value for sound pressure level. We see no reason to maintain such artificial distinction and perceive a clear simplicity advantage in adopting a single value for all media in the present context. We also see no benefit in perpetuating the use of anthropocentric values in planetary exploration, and therefore suggest adoption of 1 μPa, 1 pW and 1 pW/m^2 as suitable reference values for sound pressure level, sound power level and sound intensity level, respectively, in all fluid media.

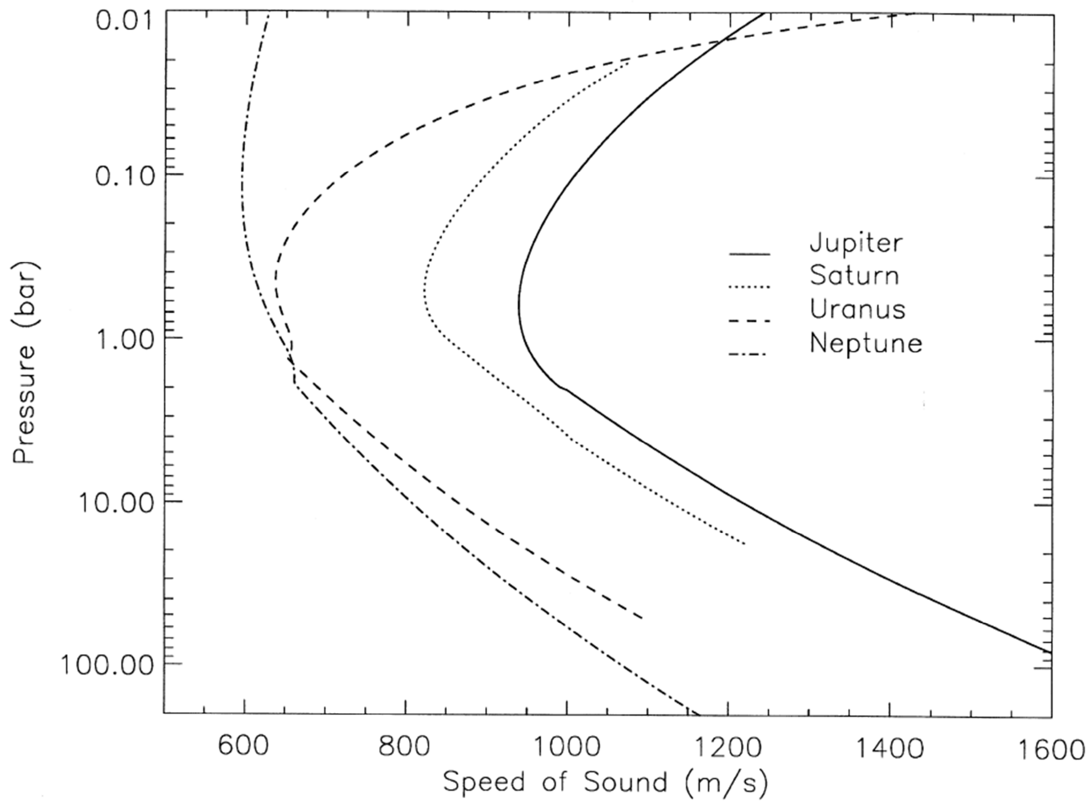

Figure 1. Theoretical sound speed profiles for Jupiter, Saturn, Uranus, Neptune, calculated assuming ideal gas conditions [35]. The significance of 1 bar (100 kPa) is that it corresponds approximately to atmospheric pressure on Earth. Reproduced from Ref. [35].

4. Conclusions

The international standard reference value of sound intensity, equal to 1 pW/m^2, is rarely used in underwater acoustics, if ever. Instead the reference intensity used depends on an unspecified value of the impedance of seawater, leading to a small ambiguity for calculations in Earth's oceans.

Given that acoustics provides by far the most useful radiation for sensing at distance in liquid oceans, it would be inconceivable not to equip exploratory missions to Titan and other icy bodies with sonar. The ambiguities encountered on Earth are amplified by the exotic conditions found on moons and planets. Given the huge investment in resource to undertake such a mission, and the ~7 year transit time of a probe to the gas giants, it would be regrettable if avoidable errors in concepts were to prevent the successful acquisition or interpretation of mission data. The purpose of this paper is to avoid one such error in the acoustical systems. The ISO 18405 sonar equations avoid the ambiguity by defining individual terms in the sonar equation in terms of ratios of mean-square sound pressure instead of equivalent plane-wave intensity. Application of these new sonar equations to planetary exploration, together with harmonised reference values for gases and liquids would provide an opportunity to start with a clean slate.

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