Recommendations for calculating sound speed profiles from field data

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Defence R&D Canada – Atlantic
Technical Memorandum
DRDC Atlantic TM 2013-156
November 2013

Abstract

Underwater acoustic propagation models rely on accurate environmental inputs in order to provide reliable predictions of transmission loss and reverberation level. One of the most critical environmental parameters in a propagation model is the vertical sound speed profile (SSP). Using a set of 40 conductivity, temperature, and depth (CTD) measurements, three common techniques of deriving SSPs from field-measured data were investigated to determine whether the choice of technique had an effect on modelled transmission loss (TL): direct measurements of the sound velocity profile, SSPs calculated from expendable bathythermograph (XBT) temperature profiles assuming constant salinity, and SSPs calculated from XBT temperature profiles with an estimated salinity profile derived from a nearby expendable sound velocimeter (XSV) profile. Differences in TL results among the different techniques were likely due to the difference in sound speed gradient at the critical depths just above the sound speed minimum. Based on these results, the preferred method for acquiring multiple SSPs would be to use either CTD or XSV profiles. If XBT profiles are used, assuming a constant salinity avoids the introduction of unphysical values for salinity (and thus the density) that frequently results from the current practice of using a 'nearby' XSV drop to estimate a salinity profile; alternatively, the estimated salinity profile should be smoothed to remove obvious outliers before using it to calculate SSPs.

Résumé

La fiabilité des prévisions de la transmission et de l'intensité de la réverbération des modèles de propagation acoustique sous l'eau dépend de la précision des données environnementales. Le profil vertical de la vitesse du son (PVS) est l'un des paramètres environnementaux les plus critiques des modèles de propagation. À partir d'un ensemble de 40 mesures de conductivité, température et profondeur (CTP), nous avons analysé trois techniques répandues de calcul des PVS à partir de données réelles afin d'établir si le choix de la technique avait un effet sur les pertes de transmission modélisées : des mesures directes du PVS, des PVS calculés à partir de profils de température captés par un bathythermographe largable (XBT) en supposant une salinité constante, et des PVS calculés à partir de profils de température obtenus par XBT et d'un profil de salinité capté à proximité par un célérimètre largable (XSV). Les écarts dans les pertes de transmission entre les différentes techniques découlent probablement des différences dans le gradient des vitesses du son aux profondeurs critiques, juste au-dessus de la vitesse du son minimale. Les résultats nous indiquent que les meilleures méthodes pour obtenir de multiples PVS sont les profils CTP ou par XSV. Si on utilise des profils obtenus par XBT, l'hypothèse de la salinité constante évite d'introduire des valeurs non physiques de salinité (donc de densité) qui découlent de la pratique courante d'utiliser les données d'un XSV déployé dans les environs pour estimer le profil de salinité ; autrement, le profil estimé de la salinité devrait être lissé pour en retirer les valeurs apparemment aberrantes avant de calculer le PVS.

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Executive summary

Recommendations for calculating sound speed profiles from field data

Cristina D. S. Tollefsen; DRDC Atlantic TM 2013-156; Defence R&D Canada –Atlantic; November 2013.

Background: Underwater acoustic propagation models rely on accurate environmental inputs in order to provide reliable predictions of transmission loss and reverberation level. One of the most critical environmental parameters in a propagation model is the vertical sound speed profile (SSP). Measurements of SSPs are ideally performed using a sound velocimeter or a conductivity-temperature-depth (CTD) profiler. However, in practice SSPs are frequently measured using an expendable bathythermograph (XBT), which measures only temperature. The user must make assumptions about salinity in order to calculate the SSP. The resulting errors in SSP may affect subsequent transmission loss (TL) predictions.

Principal results: Using a set of 40 conductivity, temperature, and depth (CTD) measurements, three common techniques of deriving SSPs from field-measured data were investigated to determine whether the choice of technique had an effect on modelled transmission loss: direct measurements of the sound velocity profile, SSPs calculated from expendable bathythermograph (XBT) temperature profiles assuming constant salinity, and SSPs calculated from XBT temperature profiles with an estimated salinity profile derived from a nearby expendable sound velocimeter (XSV) profile. Differences in TL results among the different techniques were likely due to the difference in sound speed gradient at the critical depths just above the sound speed minimum.

Significance of results: Based on these results, the preferred method for acquiring multiple SSPs would be to use either CTD or XSV profiles. If XBT profiles are used, assuming a constant salinity avoids the introduction of unphysical values for salinity (and thus the density) that frequently results from the current practice of using a ‘nearby’ XSV drop to estimate a salinity profile; alternatively, the estimated salinity profile should be smoothed to remove obvious outliers before using it to calculate SSPs.

Future work: Additional opportunities to acquire CTD measurements in conjunction with TL trials would allow for comparison of modelled and measured TL and may provide further insight into best practices for calculating SSPs from field data.

Sommaire

Recommendations for calculating sound speed profiles from field data

Cristina D. S. Tollefsen ; DRDC Atlantic TM 2013-156 ; R & D pour la
defense Canada – Atlantique ; novembre 2013.

Contexte : La fiabilité des prévisions de la transmission et de l'intensité de la réverbération des modèles de propagation acoustique sous l'eau dépend de la précision des données environnementales. Le profil vertical de la vitesse du son (PVS) est l'un des paramètres environnementaux les plus critiques des modèles de propagation. Les meilleures mesures des PVS sont réalisées à l'aide d'un célérimètre ou d'une sonde de conductivité, température, profondeur (CTP). Or, en pratique, on mesure souvent les PVS à l'aide d'un bathythermographe largable (XBT) qui ne capte que la température. L'utilisateur doit alors faire des hypothèses sur la salinité pour calculer le PVS. Les erreurs résultantes dans le PVS peuvent affecter les prévisions subséquentes de pertes de transmission.

Résultats principaux : À partir d'un ensemble de 40 mesures de conductivité, température et profondeur (CTP), nous avons analysé trois techniques répandues de calcul des PVS à partir de données sur le terrain afin d'établir si le choix de la technique avait un effet sur les pertes de transmission modélisées : des mesures directes du PVS, des PVS calculés à partir de profils de température captés par un bathythermographe largable (XBT) en supposant une salinité constante, et des PVS calculés à partir de profils de température obtenus par XBT et d'un profil de salinité capté à proximité par un célérimètre largable (XSV). Les écarts de perte de transmission entre les différentes techniques découlent probablement des différences dans le gradient des vitesses du son aux profondeurs critiques, juste au-dessus de la vitesse du son minimale.

Importance des résultats : Les résultats nous indiquent que les meilleures méthodes pour obtenir de multiples PVS sont les profils obtenus par sonde CTP ou avec un célérimètre largable (XSV). Si on utilise des profils obtenus par XBT, l'hypothèse de la salinité constante évite d'introduire des valeurs non physiques de salinité (donc de densité) qui découlent de la pratique courante d'utiliser les données d'un XSV déployé dans les environs pour estimer le profil de salinité ; autrement, le profil estimé de la salinité devrait être lissé pour en retirer les valeurs apparemment aberrantes avant de calculer les PVS.

Travaux futurs : Des occasions supplementaires de prendre des mesures de CTP en conjonction avec des essais sur la perte de transmission nous permettraient de comparer les pertes de transmission modelisees a celles mesurees et apporteraient donner un eclairage supplementaire sur les meilleures pratiques du calcul des PVS a partir des donnees prises sur le terrain.

Acknowledgements

The author would like to thank Sean Pecknold for propagation modelling support.

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1 Introduction

Underwater acoustic propagation models rely on accurate environmental inputs in order to provide reliable predictions of transmission loss and reverberation level. One of the most critical environmental parameters in a propagation model is the vertical sound speed profile (SSP). Measurements of SSPs are ideally performed using a sound velocimeter or a conductivity-temperature-depth (CTD) profiler. In the former case the SSP is measured directly while in latter case, the salinity, temperature, and depth can be used to accurately calculate the SSP.

However, in practice SSPs are frequently measured using an expendable bathythermograph (XBT), which measures only temperature and requires the user to make assumptions about salinity in order to calculate the SSP. It is common to use several XBT profiles in conjunction with a single nearby profile acquired using an expendable sound velocimeter (XSV). When using XBTs and XSVs it necessary to make some assumptions about the water column properties that may not be appropriate in all situations. The remainder of this document will explore some of the more common assumptions used and discuss how to determine when particular assumptions are appropriate.

2 Theory

The speed of sound in seawater is a complicated function of temperature T, depth z, and salinity S. Depending on the specific situation, approximations to the full equation are generally adequate for acoustic propagation modelling. For example, in water depths of 1000 m or less, the following equation [1] can be used to calculate sound speed[1] :

$$\begin{aligned} c(T,S,z) = 1449.2 + 4.6T - 0.055T^2 + 0.0029T^3 \\ +(1.34 - 0.01T)(S-35) + 0.016z \end{aligned} \tag{1}$$

where T is the temperature in °C, S is the dimensionless salinity (frequently quoted as Practical Salinity Units, or PSU), and z is the depth in m. From Equation 1 it is evident that the sound speed depends most strongly on T, with a weaker dependence on S and z.

In practice, it is common in underwater acoustics to calculate sound speed profiles using an XBT profile $T(z)$, with the assumption that S is constant throughout the water column. Typically, for any given propagation experiment, several XBT profiles are used in conjunction with a single XSV profile. The XSV profile $c(z)$ is then paired with the nearest XBT profile $T(z)$ and the two profiles are used with Equation 1 to estimate a salinity profile $S_{est}(z)$ [2]. The estimated salinity profile $S_{est}(z)$ is then used along with $T(z)$ from the XBTs to estimate the sound speed profile $c_{est}(z)$ at each location where an XBT drop was taken [2].

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[1] Valid for $0 < T[°C] < 32$, $22 < S[\text{PSU}] < 45$, $0 < z[\text{m}] < 1000$.

The assumption made when using $T(z)$ from and XBT and $c(z)$ from an XSV to calculate $S_{est}(z)$ is that the XBT and XSV were dropped 'close enough' together that they were sampling essentially the same water column. Unfortunately, in coastal areas with significant horizontal variability including (but not limited to) internal waves and tides, it is difficult to define 'close enough'.

For example, Figure 1a is a plot of $T(z)$ from an XBT and Figure 1b is a plot of $c(z)$ from an XSV separated by a range of 250 m, which is typical of field data acquired during acoustic propagation experiments. Figure 1c is a plot of the salinity profile $S_{est}(z)$ calculated using Equation 1. Close examination reveals that the thermocline on the XBT profile (Figure 1a) is not at precisely the same depths as the regions of large sound speed gradient from the XSV profile (Figure 1b): the thermocline is between 35 and 38 m depth, while the greatest sound speed gradient lies between 38 and 40 m depth. As a result, there are large deviations in the calculated values of $S(z)$ between 35 and 40 m depth. Similar effects can be seen between 55 and 80 m depth. It is impossible to know whether the difference in thermocline depth is caused by the quoted $\pm 2\%$ inaccuracy in depth estimates for XBTs and XSVs [3], or a true difference in the water column properties being profiled.

Figure 1d is a profile of the water density[2] σ_t calculated [4] using the temperature profile in Figure 1a and the salinity profile in Figure 1c. Stability in the water column would require density to increase monotonically with depth; however, there are large deviations in density at 40 m and between 55 and 80 m depth. Either there is substantial vertical mixing occurring (unlikely given the temperature stratification seen in Figure 1a) or the spatial separation of the two profiles is large enough that matching up the $T(z)$ and $c(z)$ profiles for the calculation of $S_{est}(z)$ is not physically justified.

The situation is even more extreme when the XBT and XSV pairs are farther apart. Figure 2 shows the same steps in the calculation process as Figure 1 except that the XBT and XSV are separated by 2.4 km, again, a distance that is not uncommon for field data. The temperature profile has a sharp minimum at 50 m depth, while there are two sound speed minima at 30 m and 40 m depth. The resulting $S_{est}(z)$ profile in Figure 2c has clearly unphysical values for salinity in the same region, ranging from 15 to 42 PSU. Similarly, the calculated density in Figure 2d indicates that there should be substantial vertical mixing throughout the water column, again suggesting that matching up two profiles separated by such a large distance is not physically justifiable.

However, given the practical limitations of cost and time that plague most field measurements, some guidance is needed. If only XBT measurements are available, which is the better approach: to assume a constant value for S or to calculate $S_{est}(z)$ if possible? Furthermore, what effect does the choice of S and subsequent calculation of SSP have on propagation modelling?

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[2] $\sigma_t = (\rho(S, T, p = 0) - 1000)$, where S is salinity, T is temperature, and $p = 0$ implies that the density is calculated at atmospheric pressure rather than at depth

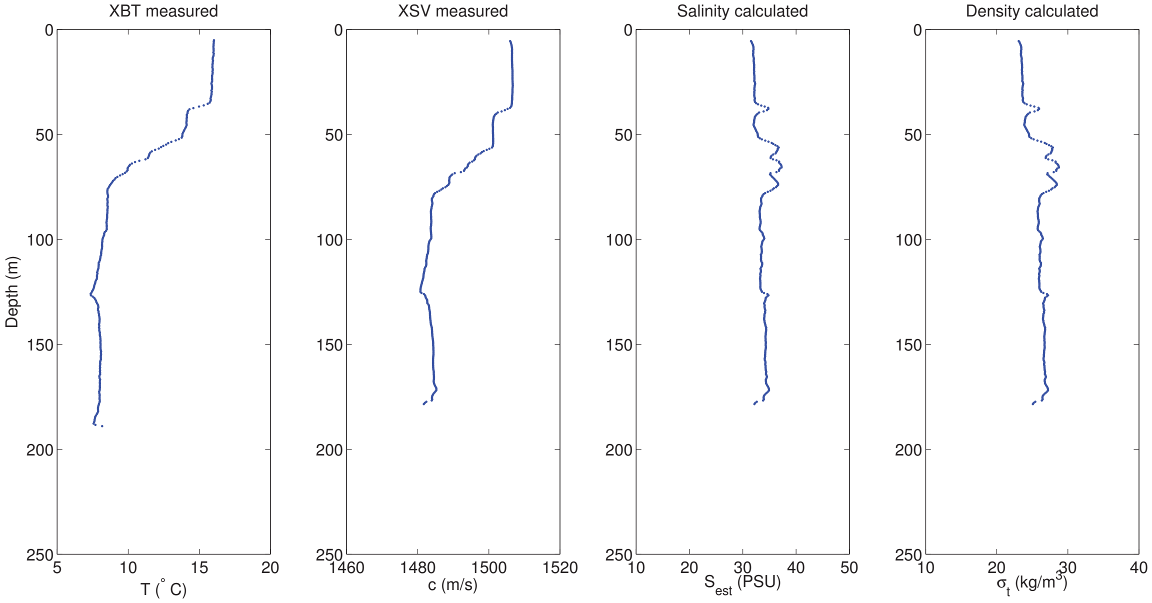

Figure 1: *Profiles taken 250 m apart of (a) temperature, measured by an XBT, (b) sound velocity, measured by an XSV, (c) salinity, estimated using Equation 1 and the profiles (a) and (b), and (d) the density ($\sigma_t = \rho(S,T,0) - 1000$) calculated from the profiles in (a) and (c).*

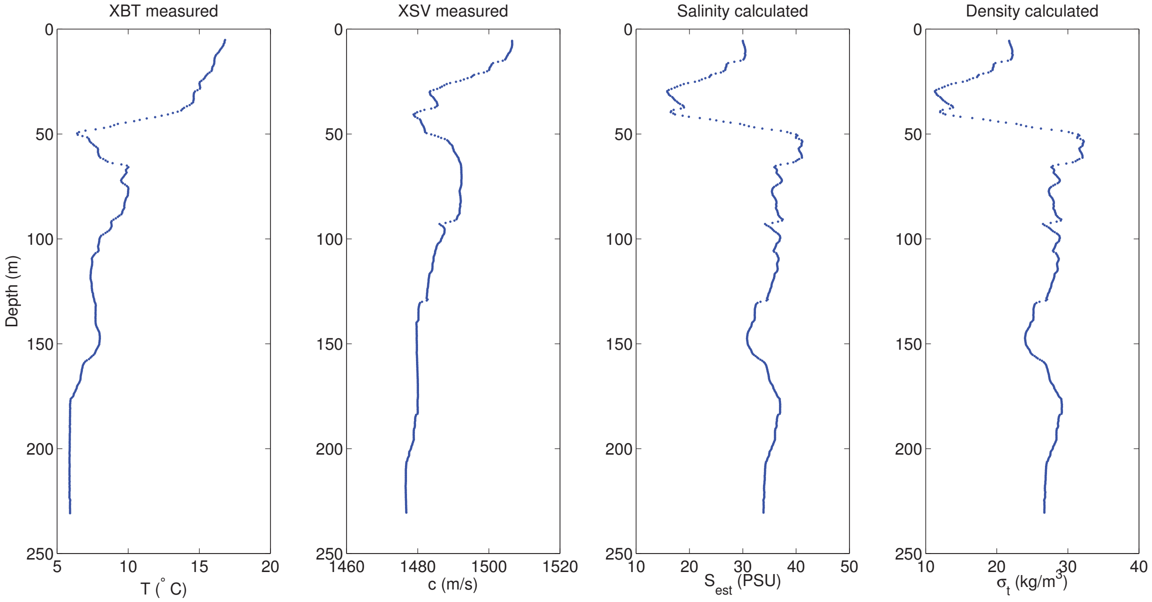

Figure 2: *Profiles taken 2.4 km apart of (a) temperature, measured by an XBT, (b) sound velocity, measured by an XSV, (c) salinity, calculated using Equation 1 and the profiles (a) and (b), and (d) the density ($\sigma_t = \rho(S,T,0) - 1000$) calculated from the profiles in (a) and (c).*

In order to answer these questions, a dataset consisting of 40 CTD profiles was used to simulate the effects of using pairs of XBT and XSV profiles to estimate the salinity profile. The resulting SSPs were used as inputs into a propagation model to determine what the effect would be on modelled transmission loss (TL).

3 Methods

Temperature, salinity, and depth were measured using a CTD sensor deployed from a Moving Vessel Profiler (MVP) on Canadian Forces Auxiliary Vessel (CFAV) Quest. The measurements were made along a 30-km track on 3 Nov 2009 as part of sea trial Q325 in the Emerald Basin (43.75° N, 62.75° W). The bathymetry consisted of a sloping, soft bottom that rose from 260 m to 95 m depth along the track. A total of 40 CTD profiles were acquired along the track.

The raw CTD profiles ($T(z)$, $S(z)$, and z) were averaged into 2-m depth bins. The 40 measured CTD profiles were used in three separate model scenarios, intended to simulate different ways of using CTD, XBT, and XSV profiles:

(A) **True c:** The SSP was calculated directly from measurements of T, S, and z, and then smoothed in depth with a 10-m moving average. The intent was to simulate a scenario where either multiple CTD profiles or directly-measured SSPs from a sound velocimeter were available.

(B) **Constant S:** The temperature profiles $T(z)$ were smoothed in depth with a 10-m moving average. The average measured salinity over all the profiles ($S = 33.6$ PSU) was calculated and then used with $T(z)$ to calculate the SSPs. The intent was to simulate using a series of XBTs used with a constant value for S.

(C) **S profile:** A temperature profile and an XSV-derived SSP spaced 754 m apart were used to estimate a salinity profile $S_{est}(z)$, which was then used with the remaining (smoothed) temperature profiles to calculate $c_{est}(z)$. The intent was to simulate using a series of XBTs with a single XSV profile that was used to estimate a salinity profile.

The SSPs for each of the scenarios A-C are plotted in Figure 3.

Acoustic transmission loss modelling was performed using BellhopDRDC [5, 6], a customized version of the well-known Bellhop transmission loss model [7]. The model was run in incoherent mode at a frequency of 1200 Hz, with source depths of 52 m and 72 m, to correspond with the TL experiment [8] that took place at the same time as the CTD profiles were collected. A range-independent bottom type (clayey silt) was used in order to isolate the effect of the SSPs on TL. The model was run to a range of 30 km for receiver depths from 0 to 260 m. The bathymetry used in the model was extracted from the

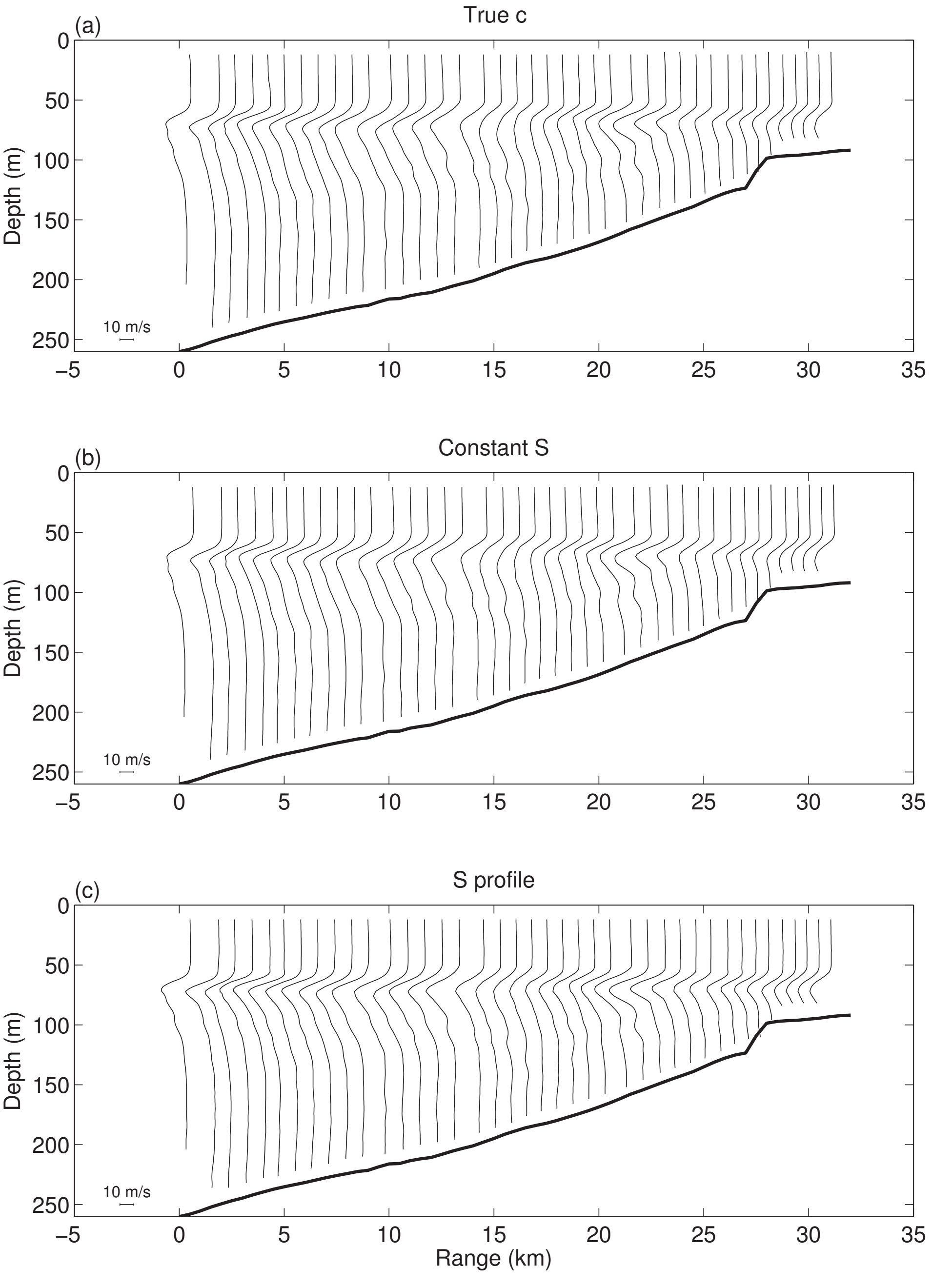

Figure 3: *SSPs calculated as described in Section 3: (a) Scenario A (true c), (b) Scenario B (constant S), (c) Scenario C (S profile). The bottom is indicated as a thick black line.*

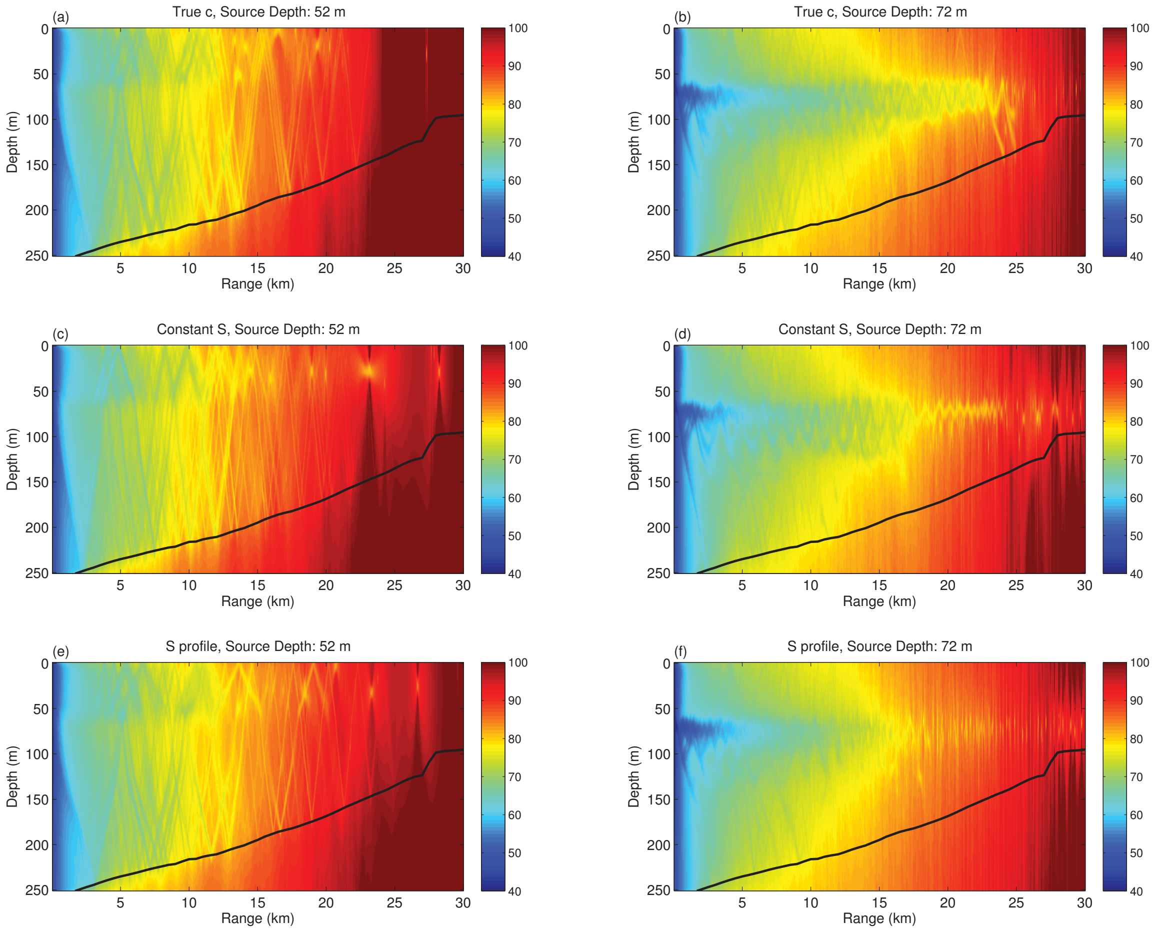

Figure 4: *Full-field incoherent TL as a function of range and depth for 52-m source depth (left column) and 72-m source depth (right column): (a) and (b) Scenario A (true c), (c) and (d) Scenario B (constant S), (e) and (f) Scenario C (S profile).*

Non-Acoustic Data Acquisition System (NADAS) file, which logged the bottom depth as measured aboard CFAV Quest.

4 Results and Discussion

Figure 4 is a plot of the full-field modelled TL for each SSP scenario and source depths of 52 m (right-hand column) and 72 m (left-hand column). For the 52-m source depth, modelled TL is qualitatively similar for all three scenarios up to a range of 20 km, at which point the modelled TL begins to diverge. All three scenarios result in a focusing effect to some extent, though it is strongest for Scenario B. For the 72-m source depth Scenario A results in a strong channel around 75 m depth that is somewhat smeared out for Scenarios B and C, and the differences in TL increase further beyond 25 km range.

Modelled TL was extracted for receiver depths of 25 m, 50 m, and 75 m in order to observe the TL for receivers above, near, and below the sound speed minimum. Figure 5 contains plots of TL as a function of range for receiver depths of 25 m, 50 m, 75 m and source depths of 52 m and 72 m. For the 52-m source depth (Figure 5a, c, and e), the TL for all three scenarios is similar up to 20 km range, at which point the three versions of predicted TL diverge substantially and differ by up to 30 dB. The large differences among scenarios and rapid change in TL over short ranges within a scenario are due to the presence of the focusing that is visible in the full-field TL plots (Figures 4a, c, and e). For the 72-m source depths (Figure 5b, d, and f), the TL is similar for all three scenarios until about 17 km range, at which point Scenario A resulted in 4-5 dB less TL between 17 km and 23 km compared to Scenarios B and C. At ranges beyond 25 km, the TL was 5-10 dB less for the Scenario A than for Scenarios B and C.

In order to directly compare the shapes of the SSPs for each scenario, all three SSPs at each range were plotted on the same axes. Figure 6 is a representative plot of SSPs for all three scenarios at a range of 17.0 km; equivalent plots at other ranges reveal similar behaviour of SSPs with depth. The Scenario A (true c) SSP follows the Scenario C (S profile) SSP very closely at depths from the surface to 60 m, and below 80 m depth. At depths between 60 m and 80 m, as the Scenario A SSP follows the Scenario B (constant S) profile. Near 60 m and 80 m depth, the gradient for Scenario A is significantly different from the gradients in the other two scenarios. The difference in gradient is most pronounced for ranges greater than 17 km, but was present at all ranges. The small difference in gradient at the depths that most strongly affect propagation may have been sufficient to cause the difference in modelled TL observed between 17–23 km range.

5 Conclusions

The relatively common technique of using an XSV and XBT profile to estimate a salinity profile for calculating SSPs from a series of XBT measurement frequently results in unphysical values for salinity and density when the XBT-XSV pair are not ‘close enough’ together. Using a set of 40 CTD measurements, three common techniques of deriving SSPs from field-measured data were investigated to determine whether the choice of technique had an effect on modelled TL. Comparisons were made among SSPs calculated directly from CTD profiles, SSPs calculated from temperature profiles and assuming a constant salinity, and SSPs calculated using an XSV and XBT pair to estimate a salinity profile that was subsequently used to calculate SSPs from a series of temperature profiles.

A TL model was run with each set of SSPs for source depths of 52 m and 72 m. Full-field TL plots showed differences in TL at ranges beyond 20 km. TL for some receiver depths differed between the SSPs calculated from CTD data and the SSPs calculated assuming constant S or an estimated S profile. The differences were likely due to the difference in sound speed gradient at the critical depths just above the sound speed minimum.

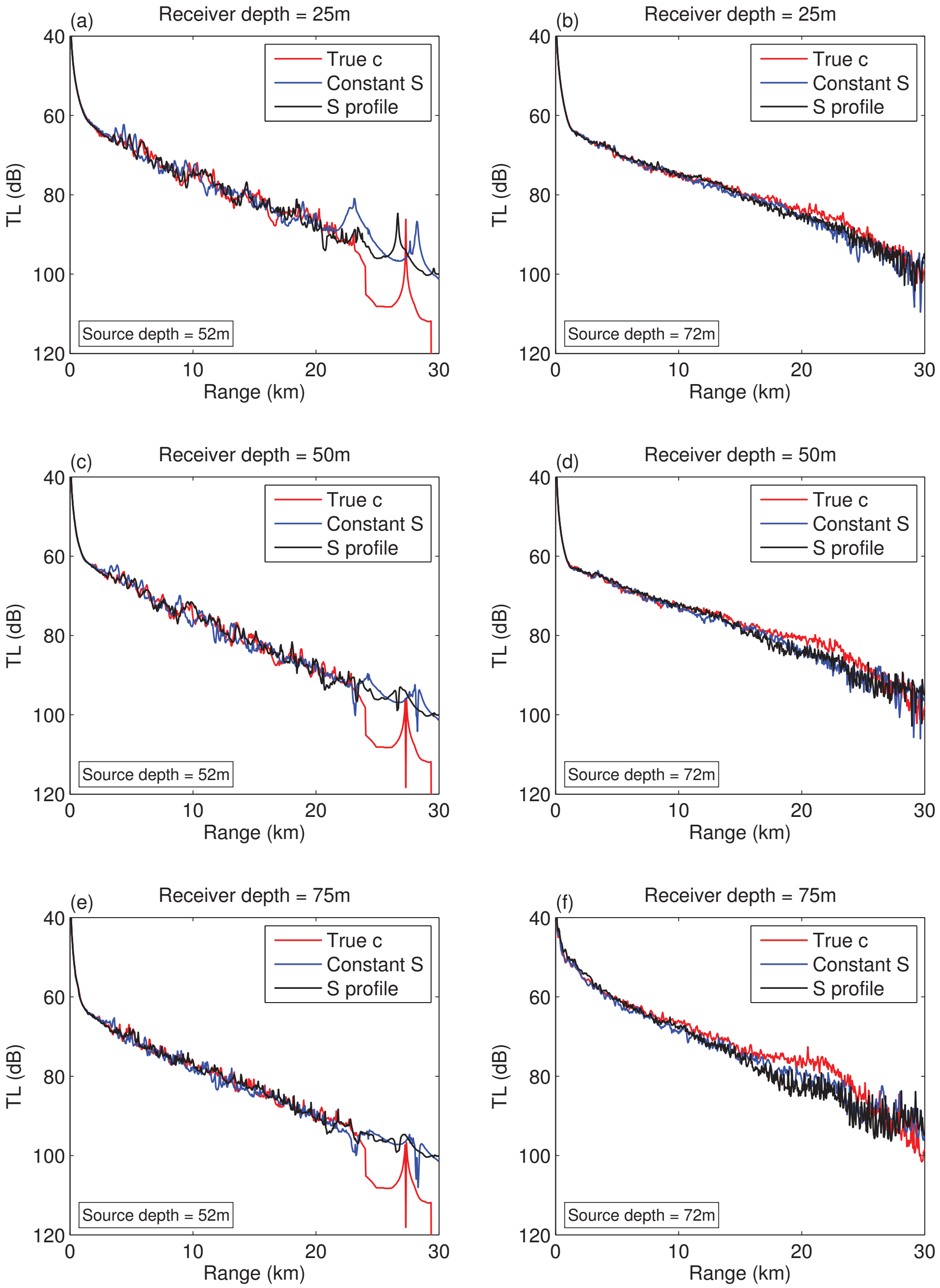

Figure 5: *Modelled TL as a function of range for (a) source depth, 52 m, receiver depth, 25 m, (b) source depth, 72 m, receiver depth, 25 m, (c) source depth, 52 m, receiver depth, 50 m, (d) source depth, 72 m, receiver depth, 50 m, (e) source depth, 52 m, receiver depth, 75 m, (f) source depth, 72 m, receiver depth, 75 m.*

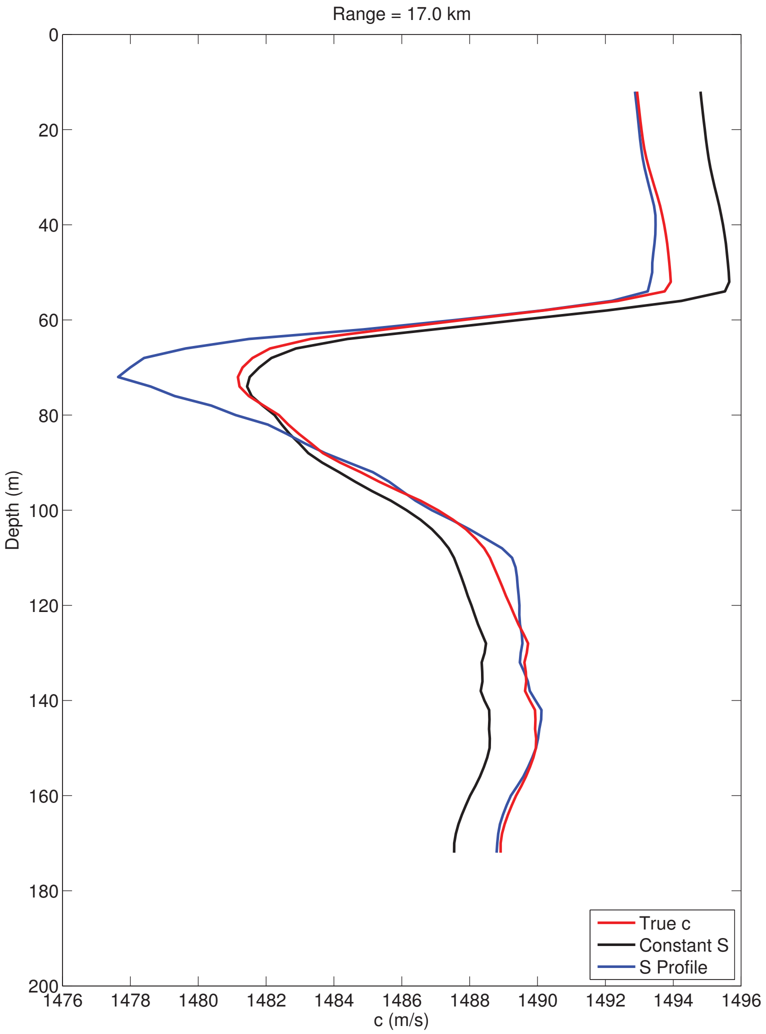

Figure 6: *SSPs for each scenario at a range of 17.0 km.*

Based on these results, the preferred method for acquiring multiple SSPs would be to use either CTD or XSV profiles to accurately calculate or measure the SSP, respectively. If XBT profiles are used, assuming a constant salinity avoids the introduction of unphysical values for salinity (and thus the density) that frequently results from the current practice of using a ‘nearby’ XSV drop to estimate a salinity profile. Another alternative would be to smooth the estimated salinity profile to remove obvious outliers before using it to calculate SSPs.

Additional opportunities to acquire CTD measurements in conjunction with TL trials would allow for comparison of modelled and measured TL and may provide further insight into best practices for calculating SSPs from field data.

Annex A: List of Abbreviations

CFAV	Canadian Forces Auxiliary Vessel
CTD	Conductivity, Temperature, and Depth
MVP	Moving Vessel Profiler
NADAS	Non-Acoustic Data Acquisition System
PSU	Practical Salinity Units
SSP	Sound Speed Profile
TL	Transmission Loss
XBT	eXpendable BathyThermograph
XSV	eXpendable Sound Velocimeter

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(Security classification of title, body of abstract and indexing annotation must be entered when document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.)

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2a. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.)

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3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

Recommendations for calculating sound speed profiles from field data

4. AUTHORS (Last name, followed by initials – ranks, titles, etc. not to be used.)

Tollefsen, C. D. S.

5. DATE OF PUBLICATION (Month and year of publication of document.)

November 2013

6a. NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.)

24

6b. NO. OF REFS (Total cited in document.)

8

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Memorandum

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

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PO Box 1012, Dartmouth NS B2Y 3Z7, Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)

11ch

9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)

DRDC Atlantic TM 2013-156

10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

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Underwater acoustic propagation models rely on accurate environmental inputs in order to provide reliable predictions of transmission loss and reverberation level. One of the most critical environmental parameters in a propagation model is the vertical sound speed profile (SSP). Using a set of 40 conductivity, temperature, and depth (CTD) measurements, three common techniques of deriving SSPs from field-measured data were investigated to determine whether the choice of technique had an effect on modelled transmission loss (TL): direct measurements of the sound velocity profile, SSPs calculated from expendable bathythermograph (XBT) temperature profiles assuming constant salinity, and SSPs calculated from XBT temperature profiles with an estimated salinity profile derived from a nearby expendable sound velocimeter (XSV) profile. Differences in TL results among the different techniques were likely due to the difference in sound speed gradient at the critical depths just above the sound speed minimum. Based on these results, the preferred method for acquiring multiple SSPs would be to use either CTD or XSV profiles. If XBT profiles are used, assuming a constant salinity avoids the introduction of unphysical values for salinity (and thus the density) that frequently results from the current practice of using a ‘nearby’ XSV drop to estimate a salinity profile; alternatively, the estimated salinity profile should be smoothed to remove obvious outliers before using it to calculate SSPs.

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transmission loss
sound speed profiles
ASPIRE
XBT
XSV
temperature
salinity