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OCEAN REMOTE SENSING WITH DIFFERENTIAL ABSORPTION SONAR

James H. Churnside

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James H. Churnside

NOAA/ERL/Wave Propagation Laboratory

Boulder, Colorado 80303

ABSTRACT

A measurement of the relative absorption of sound at two closely spaced frequencies and a simultaneous measurement of sound speed can provide a remote measurement of temperature and salinity or of temperature and pH. The former pair of parameters results when frequencies above a few kilohertz are used and the latter pair from lower frequencies. With careful model calibration, measurement accuracy depends only on signal-to-noise ratio. Values of temperature to within about 0.1°C and salinity to about 0.1 ppt should be possible if 40 dB of signal-to-noise can be obtained.

I. INTRODUCTION

The absorption of sound in sea water has been studied extensively and the general features are fairly well understood. For frequencies greater than about 500 kHz, absorption is predominantly due to viscous dissipation in the water itself [Liebermann, 1948]. Below this frequency, however, attenuation is much greater in sea water than in pure water. Liebermann [1948] postulated an ionic relaxation mechanism with a time constant of about a microsecond to explain absorption data down to about 5 kHz. The next year, Leonard et al. [1949] demonstrated that $MgSO_4$ was the source of this mechanism rather than NaCl as had been speculated by Liebermann. By comparing the theories of ionic relaxation and viscous absorption with the results of available field and laboratory measurements, Schulkin and Marsh [1962] (SM) obtained an expression for sound absorption in sea water as a function of frequency, temperature, salinity, and pressure.

The Schulkin and Marsh equation was found to underestimate the absorption of frequencies below about 5 kHz, and Thorp [1965, 1967] postulated a second relaxation mechanism to account for the low frequency data. Yeager et al. [1973] identified $B(OH)_3$ as the source of this mechanism. Equations for the total absorption accounting for all three mechanisms were advanced by Fisher and Simmons [1977] (FS) and by Francois and Garrison [1982a,b] (FG). A fourth absorption mechanism, due to a relaxation of the $MgCO_3$ ion pair, has also been identified [Fisher, 1979; Mellen et al., 1979; Mellen et al., 1980]. This reaction, whose relaxation frequency is about 10 kHz, is a relatively minor contributor to the total absorption at any frequency and has not been included in absorption equations.

The dependence of these equations on frequency as well as on the oceanographic parameters suggests that one might be able to measure the absorption at several frequencies and invert the equations to estimate the physical parameters. In practice, absorption measurements probably cannot be made with sufficient accuracy. Measurement of the absolute absorption at each frequency requires direct transmission from a calibrated source to a calibrated receiver over several paths of different length. Spreading losses must be known very accurately and signals must be averaged over a time long compared with the slowest fluctuations caused by any random inhomogeneities along the path. Garrison et al. [1983] provided an example of multiple-frequency absorption measurements of this type. Their data show clearly the large uncertainties in carefully measured absorption values that make this approach unworkable.

However, there is an alternative that may prove practical. If the ratio of the received signal powers at two closely spaced frequencies is measured, most of the calibration factors cancel and one is left with information about the difference in the absorption coefficients at the two frequencies. This also contains the information on the oceanographic parameters. Therefore, the equations for several of these ratios can be inverted to infer the physical parameters from the measured ratios. This is a much easier measurement to make. The transducers do not need to be calibrated; only their relative frequency response is required. The actual spreading losses do not need to be known as long as any frequency-dependent components, such as diffraction, can be identified. All wavelengths can be transmitted simultaneously over a single path so that averaging over all random signal fluctuations is not necessary; one can make the measurement on an instantaneous realization of path characteristics.

Differential absorption values, which are based on relative power measurements, can be obtained much more accurately than absolute absorption values, which require absolute power measurements. In addition differential absorption measurements can be combined with other techniques, such as time-of-flight sound speed measurements, and useful measurements should be possible. The precision of these measurements is not expected to be as good as those from in situ sensors. The spatial resolution will also be poorer. On the other hand, acoustic techniques can provide spatial averaged values continuously for long periods of time without fouling. Data of this nature from in situ sensors would be extremely expensive. Therefore, acoustic techniques such as differential absorption are seen as complementing rather than replacing in situ sensors.

II. ABSORPTION EQUATIONS

The Schulkin-Marsh [1962] equation for the absorption coefficient α is

$$\alpha = B \frac{f_T f^2}{f_T^2 + f^2} + C \frac{f^2}{f_T} , \qquad (1)$$

where B is the coefficient of the $MgSO_4$ absorption, C is the coefficient of the viscous absorption, f is frequency, and f_T is the relaxation frequency of the $MgSO_4$ reaction. The authors suggested

$$B = 2.3 \times 10^{-6}\ m^{-1}\ Hz^{-1}\ S(1 - 6.54 \times 10^{-4}\ atm^{-1}\ P) , \qquad (2)$$

$$C = 3.38 \times 10^{-9}\ m^{-1}\ Hz^{-1}\ (1 - 6.54 \times 10^{-4}\ atm^{-1}\ P) , \qquad (3)$$

$$f_T = 2.19 \times 10^{10}\ Hz \exp[- 3500\ K/T] \qquad (4)$$

where S is the salinity, P is the pressure, and T is the temperature. The boric acid relaxation mechanism is not included in this expression and the result is not valid for freuencies below about 5 kHz. Note also that the inclusion of the relaxation frequency in the viscous absorption term was done simply as an approximation to the temperature dependence of that process. No physical dependence is implied.

The Fisher-Simmons [1977] equation for the absorption coeficient is slightly different. They use

$$\alpha = A \frac{f_B \, f^2}{f_B^{\,2} + f^2} + B \frac{f_T \, f^2}{f_T^{\,2} + f^2} + C\, f^2 \,, \tag{5}$$

where

$$A = (1.03 \times 10^{-8} + 2.36 \times 10^{-10} {}^\circ C^{-1}\, T - 5.22 \times 10^{12} {}^\circ C^{-2}\, T^2) m^{-1}\, Hz^{-1} \tag{6}$$

$$\begin{aligned} B = {} & (5.62 \times 10^{-8} + 7.52 \times 10^{-10} {}^\circ C^{-1}\, T)\ m^{-1}\ Hz^{-1} \\ & \times (1 - 1.03 \times 10^{-3}\ atm^{-1}\ P + 3.7 \times 10^{-7}\ atm^{-2}\ P^2) \,, \end{aligned} \tag{7}$$

$$\begin{aligned} C = {} & (55.9 - 2.37\ {}^\circ C^{-1}\ T + 4.77 \times 10^{-2}\ {}^\circ C^{-2}\ T^2 \\ & - 3.48 \times 10^{-4}\ {}^\circ C^{-3}\ T^3) \times 10^{-15}\ m^{-1}\ Hz^{-2} \\ & \times (1 - 3.84 \times 10^{-4}\ atm^{-1}\ P + 7.57 \times 10^{-8}\ atm^{-2}\ P^2) \,, \end{aligned} \tag{8}$$

$$f_B = 1.32 \times 10^3\ Hz\ K^{-1}\ T \exp[- 1700\ K/T] \tag{9}$$

$$f_T = 1.55 \times 10^7\ Hz\ K^{-1}\ T \exp[- 3052\ K/T] \tag{10}$$

This equation was generated from measurements on Lyman-Fleming [1940] sea water with a constant salinity of 35 parts per thousand and a constant pH of 8. A linear dependence of B on salinity is assumed by Fisher and Simmons [1977] to compare their results to previous results, and is probably reasonable.

The Francois-Garrison equation for the absorption coefficient has the same form as the Fisher-Simmons equation of Eq. (5). Different expressions for A, B, C, f_B, and f_T are used, however. Francois and Garrison recommend using

$$A = 1.02 \times 10^{-8} \exp[1.8 \text{ pH}]/c \qquad (11)$$

where the sound speed c is approximated by

$$c = (1412 + 3.21 \text{ °C}^{-1} T + 1190 S + 0.167 \text{ atm}^{-1} P) \text{ m/s} , \qquad (12)$$

$$B = 2.468 \times 10^{-3} \frac{S}{c} (1 + 0.025 \text{ °C}^{-1} T)$$

$$\times (1 - 1.37 \times 10^{-3} \text{ atm}^{-1} P + 6.2 \times 10^{-7} \text{ atm}^{-2} P^2) , \qquad (13)$$

and

$$C = C_T(1 - 3.83 \times 10^{-4} \text{ atm}^{-1} P + 4.9 \times 10^{-8} \text{ atm}^{-2} P^2) , \qquad (14)$$

where

$$B_T = (5.684 \times 10^{-14} - 2.98 \times 10^{-15} \text{ °C}^{-1} T + 1.05 \times 10^{-16} \text{ °C}^{-2} T^2$$

$$- 1.73 \times 10^{-18} \text{ °C}^{-3} T^3) \text{ m}^{-1} \text{ Hz}^{-2} \qquad (15)$$

for $T \leqslant 20$°C and

$$B_T = (4.564 \times 10^{-14} - 1.319 \times 10^{-15} \text{ °C}^{-1} T + 1.67 \times 10^{-17} \text{ °C}^{-2} T^2$$

$$- 7.5 \times 10^{-20} \text{ °C}^{-3} T^3) \text{ m}^{-1} \text{ Hz}^{-2} \qquad (16)$$

for $T > 20$°C. They use an equation for the relaxation frequency

$$f_B = 1.5 \times 10^8 \text{ Hz } S^{1/2} \exp[-2867 \text{ K}/T] \qquad (17)$$

$$f_T = \frac{8.17 \times 10^{11} \text{ Hz} \exp[- 4580 \text{ K}/T]}{1 + 1.8 (S - 0.035)} , \qquad (18)$$

based on the work of Glotov [1964]. This formula is by far the most complete of those that are available. It includes all three of the major relaxation processes and explicitly gives temperature, salinity, pressure, and pH dependences.

III. PARAMETER ESTIMATION

The ratio of the received powers at two frequencies f_1 and f_2 is given by

$$\frac{P(f_1)}{P(f_2)} = \frac{K(f_1)}{K(f_2)} \exp\{-[\alpha(f_1) - \alpha(f_2)]z\} \tag{19}$$

where K(f) is a calibration factor that includes the calibration of the transducers and beam-spreading losses, and z is the propagation distance. Since the differential absorption $\alpha(f_1) - \alpha(f_2)$ contains the same information about the oceanographic parameters as the absolute absorption $\alpha(f)$, these parameters can be inferred from a measurement of the received power ratio. This is a much easier measurement to make than an absolute power measurement. The other qualities required are the propagation distance and the ratio of the calibration constants. For closely spaced frequencies, the calibration constant ratio should be nearly unity. The medium is non-dispersive so that spreading losses are independent of frequency. Frequency-dependent transducer characteristics can be minimized by careful design; residual effects can be measured very accurately and used in Eq. (19).

If enough different frequencies are used, equations of the type presented in the previous section can be inverted to obtain the oceanographic parameters. As an example, consider a measurement using four frequencies near the $MgSO_4$ relaxation frequency. The effects of boric acid can be neglected at these frequencies, and the three independent frequency pairs associated with four frequencies lead to three equations in absorption difference. These equations can be inverted to obtain temperature, salinity, and pressure. At lower frequencies, a five-frequency measurement around the boric acid relaxation frequency provides four equations in absorption difference that can be solved for temperature, salinity, pressure, and pH.

The accuracy with which the physical parameters can be measured depends mainly on two factors: signal-to-noise ratio (SNR) and the accuracy of the model. The limitations imposed by the former can be illustrated by considering a typical example and performing order-of-magnitude estimates of the measurement errors. We assume a system operating near the $MgSO_4$ relaxation frequency of around 100 kHz over a range of about 1 km. Three pairs of frequencies, each pair separated by about 1 kHz, are used. 40 dB of SNR at each frequency is assumed. In this example, the relative uncertainty in each power ratio measurement will be about one percent. The absorption difference will be in the 5 to 10 percent range so that the uncertainty in each absorption difference will be less than 1/2 percent. The resulting uncertainties in temperature, salinity, and pressure depend on the specific values of those parameters and on the specific frequencies chosen. For typical values, the temperature measurement error will be of the order of 0.1°C, the salinity error will be of the order of 0.1 ppt, and the pressure measurement error will be of the order of 10 atm.

The errors introduced by uncertainties in the absorption model are more difficult to address. Each of the three models is an empirical fit to available data, and errors exist in each of them. Consider, for example, the relationship of relaxation frequency on temperature, which is probably the most intensively studied of the dependences considered. This relationship is plotted in Fig. 1 for each of the three models. Considerable differences are evident. Note especially that the Francois-Garrison study, which had much more low temperature data available, is significantly different from the other two studies at low temperatures.

To see the effects these kinds of differences have on estimates of the various parameters, we can use one model to calculate the absorption and solve for the physical parameters using the other two. This has been done using the Francois-Garrison model as the baseline. The results are plotted as functions of the assumed temperature in Figs. 2-4 for one atmosphere of pressure and 35 ppt salinity. These figures show clearly that large differences exist in the three models, and that these differences can significantly affect the performance of the system. These differences are probably due to the difficulties of making absolute absorption measurements in the open ocean. This is especially true at the lower frequencies where a typical measurement might use an explosive source to generate a broad band of frequencies. The energy is assumed to initially spread spherically and then cylindrically as sound channel effects become important. The path averaged absorption measurements are compared with point measurements or even standard values of the oceanographic parameters. Measurement of the absolute asorption to within a percent is not possible under these conditions.

From the preceeding discussion, it is clear that differential absorption techniques do not provide a sensitive measurement of pressure. Fortunately, in situ pressure measurements are straightforward. Also, travel-time measurements of sound speed are routinely made, and the dependence of sound speed on temperature, salinity, and pressure is fairly well known [Wilson, 1960a,b, 1962]. The three-frequency-pair measurement is therefore probably not the optimum configuration. A better measurement scheme would combine in situ pressure sensors, a travel-time sound speed estimate, and a two-frequency differential absorption measurement.

Consider first a pair of frequencies between the boric acid and magnesium sulfate relaxation frequencies. Simultaneous measurement of travel-time and differential absorption produces two equations that depend on temperature and salinity. For the 40 dB SNR example considered previously, measurement of temperature to 0.1°C and salinity to 0.1 ppt requires a travel time measurement accurate to only about one part in 10^4, which is fairly easily obtained.

A second possibility would be to use a pair of frequencies below the boric acid relaxation frequency. The differential absorption in this case depends on pH as well as salinity. From Eqs. (11) and (12), we see that the sensitivities of absorption to changes in salinity and pH are about the same. Since pH in the oceans varies by almost a full pH unit, however, while salinity varies by only a few parts per thousand, salinity effects can be neglected. The resulting measurement of differential absorption and sound speed will provide values of temperature and pH. At lower frequencies, the absorption is lower and longer propagation distances are required to obtain the same differential absorption with the same relative frequency spacing. A distance of 1000 km might be typical of this type of measurement. At this distance, the effects of the sound channel need to be considered. The sound channel is non-dispersive, so that the calibration factor ratio in Eq. (19) is not affected. However, the sound channel will cause the depth of an acoustic wave to vary as it propagates from the transmitter to the receiver and the path averaged measurements that result will include a weighted average over depth that may not be desirable. Fortunately, the techniques of "vertical slice" tomography [Munk and Wunsch, 1979] can be used to infer vertical profiles of the oceanographic parameters from a single propagation path in the sound channel.

Finally, one might consider a pair of frequencies above the boric acid relaxation and a pair below to measure temperature, salinity, and pH. Because of the square-law dependence of absorption on frequency, this would be difficult on a single path. Any path long enough to provide measurable absorption levels at the lower frequencies would tend to absorb virtually all of the higher frequency energy. Separate paths for the two frequency pairs would probably be required.

IV. DISCUSSION

The combination of sound speed and differential absorption at frequencies above a few kilohertz provides path-averaged values of temperature and salinity for paths of up to the order of perhaps 10 km. Such measurements might be useful in the Greenland Sea, for example, where the temperature-salinity relationships do not allow reliable estimation of salinity from temperature measurements. Tomographic arrays of measurements would allow spatial details smaller than the propagation paths to be resolved, and mixing of salt and fresh waters could be studied in some detail. At lower frequencies, and over longer ranges, temperature and pH can be monitored. This could provide information pertinent to the CO_2 cycle over large sections of the oceans. Again, tomographic technique could provide spatial detail.

One advantage of acoustic remote sensing techniques over in situ measurements is the path-averaged nature of the measurement. Care must be taken to ensure that an in situ measurement is made at a position that is representative of the area of interest. However, a much more compelling reason to investigate acoustic techniques is the economic advantage of tomographic arrays [Munk and Wunsch, 1979]. With conventional techniques, N moorings provide N data points. Using acoustic tomography, N moorings can produce an array of N(N-1)/2 propagation paths and the inversion yields N(N-1)/2 data points. A single measurement can be obtained with one in situ sensor or two acoustic transducers (a source and a receiver), and the economics would probably favor conventional techniques. Three data points require three moorings with either approach. However, with larger numbers of moorings, much more data can be obtained using tomography; with ten moorings, for example, 45 data points can be obtained.

Note also that the relative absorptions can be measured using sound reflected from the sea floor or some other surface as long as the frequency dependence of the scattering process is known; the absolute reflectivity of the object does not have to be known. It is tempting to consider relative absorption measurements with volume reverberation as a signal source since we do not need to know the scattering strength. Determination of the frequency dependence of the scattering process would be required, however, and this would be extremely difficult.

The available absorption models are not sufficient, however, and a large measurement program is required before these techniques can be implemented. The models described in Section II have sacrificed accuracy for global coverage, both geographically and in frequency. Such global coverage is not required for differential purposes. What we require are regional models over very limited frequency ranges. These models should be based on differential absorption measurements at closely spaced frequencies to eliminate the effects of spreading losses that add uncertainty to absolute absorption measurements.

The model calibration measurements should be made in areas where the oceanographic parameters are very uniform. These models can then be used in areas of spatially varying characteristics to make full use of the spatial averaging nature of acoustic measurements.

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FIGURE CAPTIONS

Figure 1. $MgSO_4$ relaxation frequency f_T vs. temperature T predicted by the SM and FS models and by the FG model using a salinity of 0.035.

Figure 2. Estimated vs. assumed temperature T from SM and FS models using absorption calculated from the FG model with 1 atm pressure and 0.035 salinity.

Figure 3. Estimated salinity vs. assumed temperature from SM and FS models using absorption calculated from the FG model with 1 atm pressure and 0.035 salinity.

Figure 4. Estimated pressure vs. assumed temperature from SM and FS models using absorption calculated from the FG model with 1 atm pressure and 0.035 salinity.

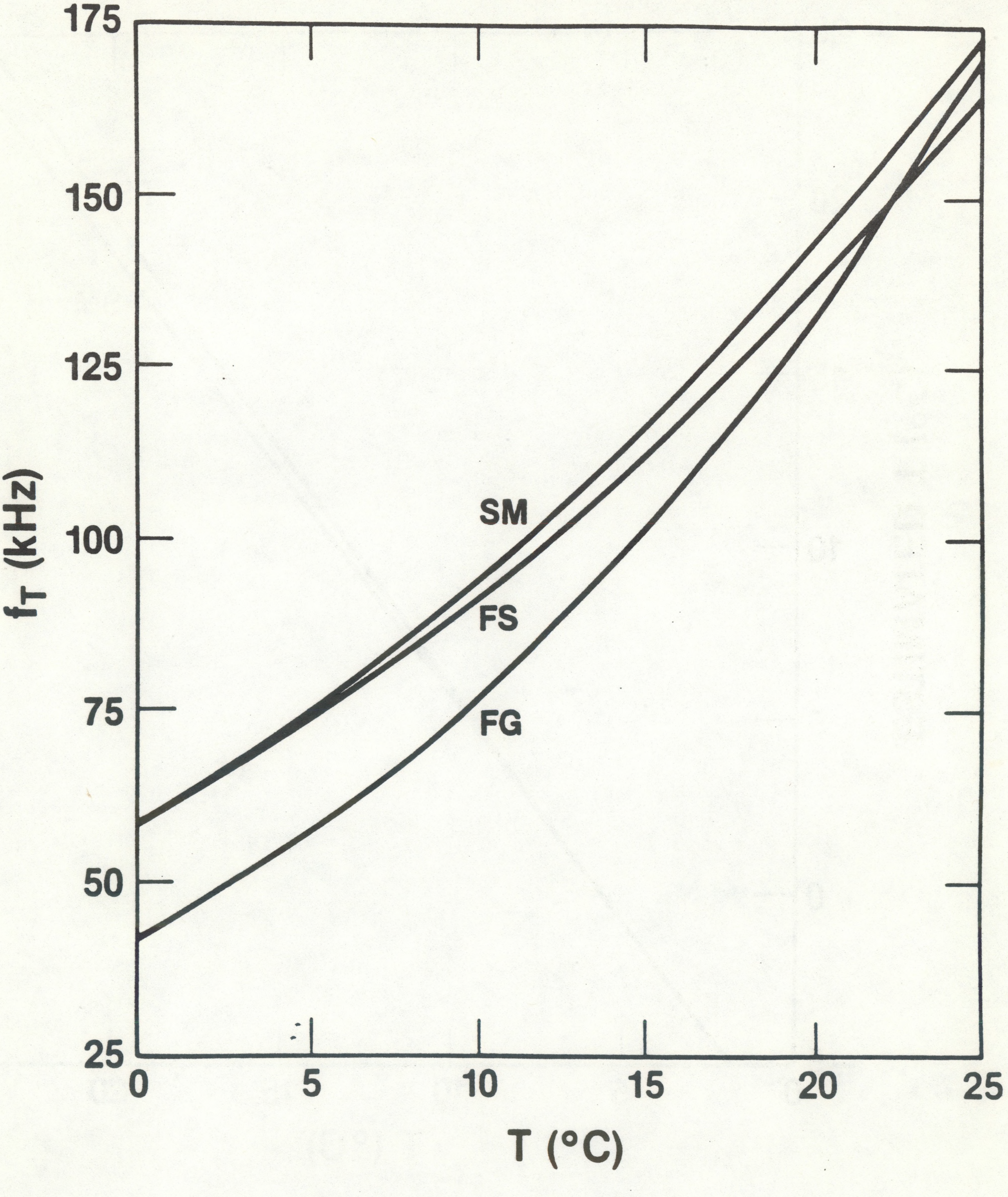

Figure 1. $MgSO_4$ relaxation frequency f_T vs. temperature T predicted by the SM and FS models and by the FG model using a salinity of 0.035.

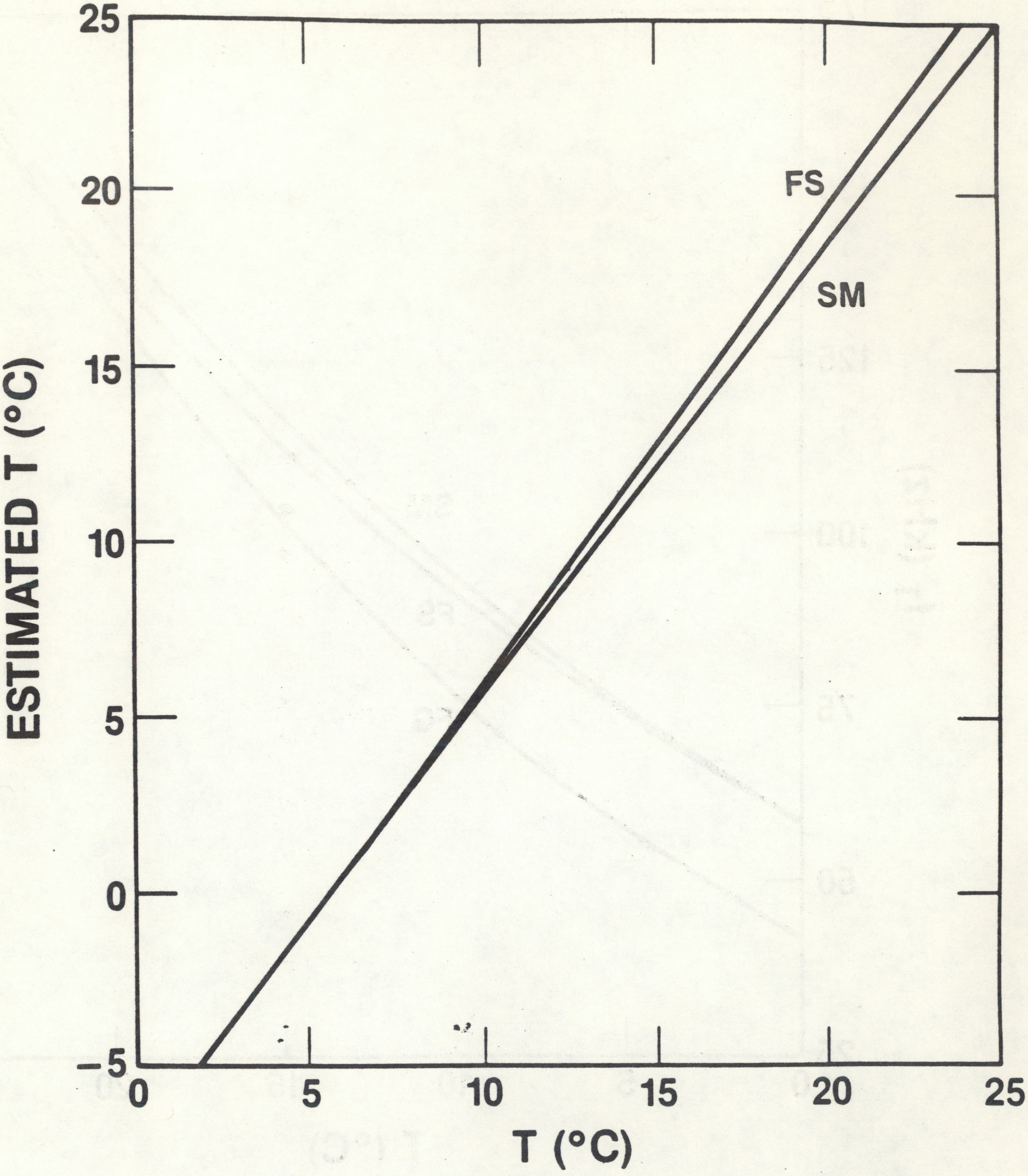

Figure 2. Estimated vs. assumed temperature T from SM and FS models using absorption calculated from the FG model with 1 atm pressure and 0.035 salinity.

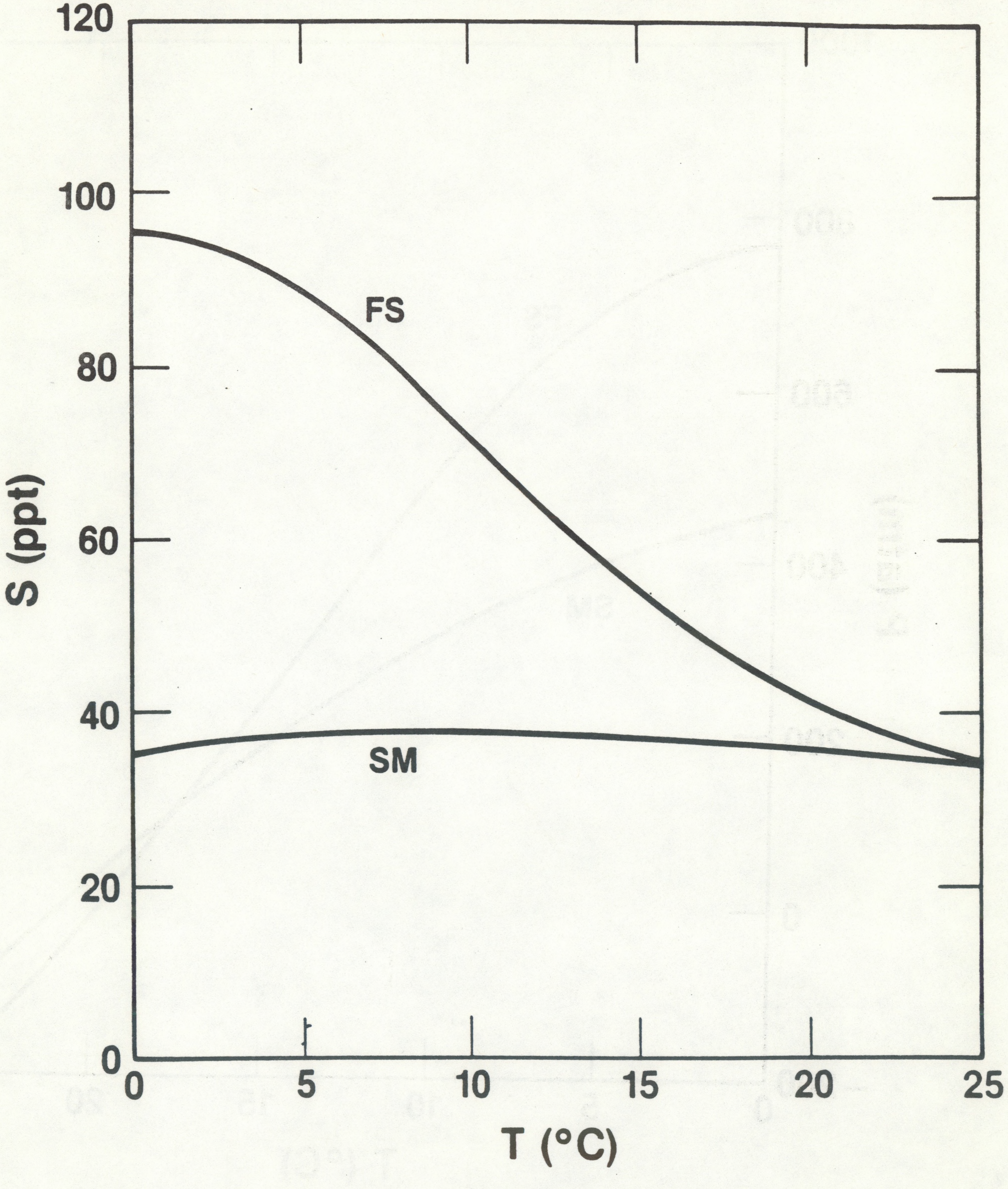

Figure 3. Estimated salinity vs. assumed temperature from SM and FS models using absorption calculated from the FG model with 1 atm pressure and 0.035 salinity.

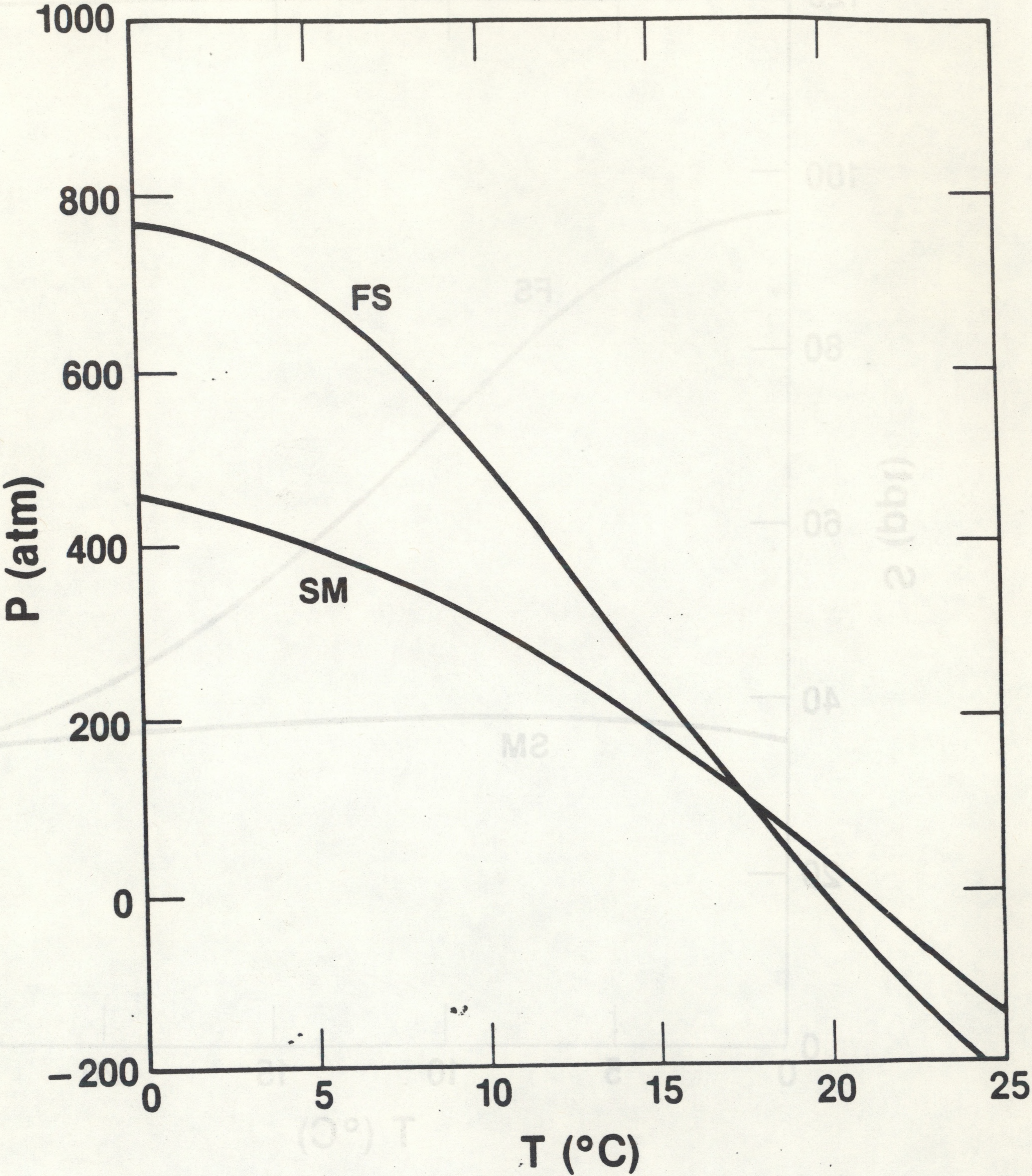

Figure 4. Estimated pressure vs. assumed temperature from SM and FS models using absorption calculated from the FG model with 1 atm pressure and 0.035 salinity.