PRACTICAL ASPECTS OF ACOUSTIC EMISSION SOURCE LOCATION BY A WAVELET TRANSFORM - Appendices

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Appendix A: Discussion of Y-intercept Values for Computed Slope-based Group Velocities

Table 1 in the main article body includes a column called the "y-axis intercept, mm". This is the standard intercept that corresponds to zero time for the straight line that fits the three data points in the plot of distance versus arrival time. As is apparent from the table, this value is not zero for the 0° radiation angle data. A previous publication [1] associated this non-zero intercept with the fact that Lamb waves do not start instantaneously at the dipole source, but instead these waves can be distinguished only after the bulk waves have propagated a distance of some ten or more plate thicknesses from the source position [10]. Thus, the authors believe that the non-zero intercept arises from the need for propagation over a certain distance to develop the Lamb modes, which then can be observed to propagate at their associated group velocities. Table 1 indicates much wider variations in the y-intercept values as compared to the group velocities for the primary WT results. For example, the range of the slope-based intercept for A_0 at 60 kHz is about 30 % as compared to only about 3.2 % for the group velocities.

Additional observations can be made when considering the data for radiation angles other than 0°. Since the slope-based group velocities from the secondary and tertiary frequencies data were nearly the same as those from the primary frequency data, the y-intercept values from these data were also compared to the primary-based intercept values. In general, the comparison was not as favorable, even where data for $r^2 < 0.9997$ were eliminated. For example, the range of y-intercepts for the secondary and tertiary values for A_0 at 522 kHz varied from -1.7 to 4.5 mm (for 16 values). This wider range contrasts with the primary y-intercept values of 1.3 to 3.2 (for 11 values). Upon closer examination, it was found that the biggest contributor to this wider range was the tertiary-based values. If only the secondary-based values were used, the range was

Table A-1 Average y-intercept values and coefficients of sample dispersion for two greatest of three WT fractions for selected cases for radiation angles other than 0°

Frequency (kHz)	Mode (* indicates principal mode at this frequency)	Calculated average y-intercept (mm)	Coefficient of sample dispersion (%)	Number of cases
60	A_0 *	17	9	43
60	S_0	na	na	na
270	S_0 *	-6.5	23	3
270	A_0	-3.1	-- (all intercept values are equal)	6
522	S_0 *	2.0	30	15
522	A_0	-1.3	15	6

reduced to 2.0 to 3.2 mm (for 8 values). Thus, since even the primary-based y-intercept values had a wider percentage range than the associated group velocity values, we chose to reduce the database before calculating average values. Table A-1 gives the results when at least 2 of the 3 WT fractions for a case were greater than 0.5. Taking note of the rather large coefficients of sample dispersion (expressed as a percentage) in table A-1 in comparison to those in table 3, it is clear that the y-intercept values are not as certain for radiation angles other than 0° as are the velocities. Thus, if these values are used in calculations, the potential for errors is present.

Appendix B: Computation Approach for Signal Ranges

One may use standard algebra to compute a slope for a given set of x,y data pairs. The standard form for such an equation is

$$y = mx + b, \qquad \text{(B-1)}$$

where m is the slope and b is the y-axis intercept at x = 0.

In AE signal scenario, y is the range (or distance, mm); x is the arrival time of the signal (_s); m is the group velocity (mm/_s); and b is the group velocity y-intercept (mm). The following equation applies in those cases where the "real arrival time" (i.e., equivalent to a clock starting at the source operation time) is precisely recorded:

$$R = VT + B, \qquad \text{(B-2)}$$

where R is the range, V is the group velocity, T is the real arrival time, and B is the y-intercept. The reason that B is typically not equal to zero is that an AE signal must travel a linear distance usually up to 10 plate thicknesses before Lamb waves and the associated group velocity behavior fully develops [10].

However, the typical AE measurement and waveform recording system does not record a signal until a signal magnitude threshold is crossed, and it also records a certain amount of pretrigger information for each signal, hence the source operation time is not necessarily at the very beginning of the stored waveform. Therefore, the recorded arrival time (i.e., the "measured arrival time") differs from the "real arrival time" by some time offset (i.e., an arbitrary time amount that varies for each recorded signal but which is the same for all frequencies within a given signal, and which could be either negative or positive in value). In other words, the real arrival time equals the measured arrival time ($T_{measured}$) plus a time offset (T_{offset}). Thus, the equation below is a more generalized form for measured AE signals.

$$R = V_x \left(T_{measured@x} + T_{offset}\right) + B_x, \qquad \text{(B-3)}$$

where R is the range, V is the group velocity, B is the y-intercept, and x is any particular frequency of interest.

To assist the reader in gaining a greater understanding of T_{actual} versus $T_{measured}$ and T_{offset}, Figure B-1 shows a timeline for (a) the unknown test signals used in section 10, and (b) a typical measured experimental AE signal. In it, one may see scenarios in which T_{offset} can have either a negative or positive value.

Since this effort has used three frequencies of interest, one could compute three range values for each signal (assuming one knew the proper T_{offset} for each signal), e.g., one value of R based on the velocity and arrival time information for each of the three frequencies of interest. In an ideal case, these three range values would be identical, and in the empirical case, they should be quite consistent with each other. One can use equation B-3 and solve for the arrival time, $T_{measured@x}$, (using the shortened notation $T_x = T_{measured@x}$) for each of the frequencies of interest, thus creating equations B-4, B-5 and B-6.

$$T_{60} = T_{offset} + \frac{R - B_{60}}{V_{60}} \qquad \text{(B-4)}$$

$$T_{270} = T_{offset} + \frac{R - B_{270}}{V_{270}} \qquad \text{(B-5)}$$

$$T_{522} = T_{offset} + \frac{R - B_{522}}{V_{522}} \qquad \text{(B-6)}$$

Since it is not easily possible to determine the proper T_{offset} for each signal, one may eliminate T_{offset} algebraically by combining equations for two different T_x values for the same signal (equations B-4, B-5 and B-6). Subtracting equation B-5 from equation B-4 and solving for R yields the following expression, where $R_{60/270}$ is defined as the range computed using information from the 60 kHz and 270 kHz frequencies. $R_{60/522}$ and $R_{270/522}$ are defined in a similar fashion.

$$R_{60/270} = \frac{(T_{60} - T_{270}) + \left(\frac{B_{60}}{V_{60}} - \frac{B_{270}}{V_{270}} \right)}{\frac{1}{V_{60}} - \frac{1}{V_{270}}} \qquad \text{(B-7)}$$

Similarly, combining equations B-4 and B-6 results in equation B-8.

$$R_{60/522} = \frac{(T_{60} - T_{522}) + \left(\frac{B_{60}}{V_{60}} - \frac{B_{522}}{V_{522}} \right)}{\frac{1}{V_{60}} - \frac{1}{V_{522}}} \qquad \text{(B-8)}$$

Similarly, combining equations B-5 and B-6 results in equation B-9.

$$R_{270/522} = \frac{(T_{270} - T_{522}) + \left(\frac{B_{270}}{V_{270}} - \frac{B_{522}}{V_{522}} \right)}{\frac{1}{V_{270}} - \frac{1}{V_{522}}} \qquad \text{(B-9)}$$

In attempting to compute ranges described above, one could use the theoretical values of group velocity, but that approach would not produce the most appropriate computed values. One must recognize that there is not a single absolute wavelet transform; in fact, different mother wavelets used in a WT software approach, or different choices in certain of the wavelet settings can result in different values for the peak WT magnitudes (and hence different arrival times) at the frequencies of interest for any given signal. Therefore, the most appropriate manner found for choosing values of group velocity was to use data from known signals that were processed in a WT fashion identical to that which would be used for unknown signals. Consequently, the WT data from the 150 cases of signals at the zero-degree radiation direction with known source operation times (i.e., 50 types with three distances per signal type) were used to compute average group velocities and average y-intercepts for both A_0 and S_0 modes at the three frequencies of interest. This database was used since it included more source types than the database for non-zero radiation angles. Only those instances where at least two out of the three different distances for a given signal type had WT fractions of 0.5 or greater were used to compute the averages (except for values for S_0 at 60 kHz, where all available values were necessarily used). These results are summarized in appendix table B-1.

Table B-1 Summary of average group velocities and y-axis intercepts (where signals for at least two of three distances had WT fractions of 0.5 or greater)

Mode	Frequency	Average Group Velocity (mm/_s)	# of Values Used to Compute Average Group Velocity	Std. Deviation (sample) of Group Velocity	Average Group Velocity y-axis Intercept (mm)	# of Values Used to Compute Average y-axis Intercept	Std. Deviation (sample) of y-axis Intercept
A_0	60 kHz	2.551	43	0.03	-17.2	43	1.5
A_0	270 kHz	3.133	6	0.00	-3.1	6	0.0
A_0	522 kHz	3.049	6	0.004	-1.3	6	0.2
S_0	60 kHz	5.352*	5	0.07	-27.2*	5	3.6
S_0	270 kHz	4.819	3	0.04	-6.5	3	1.5
S_0	522 kHz	1.811	15	0.03	2.0	15	0.6

*average of <u>all</u> available values, even those with WT fractions less than 0.5.

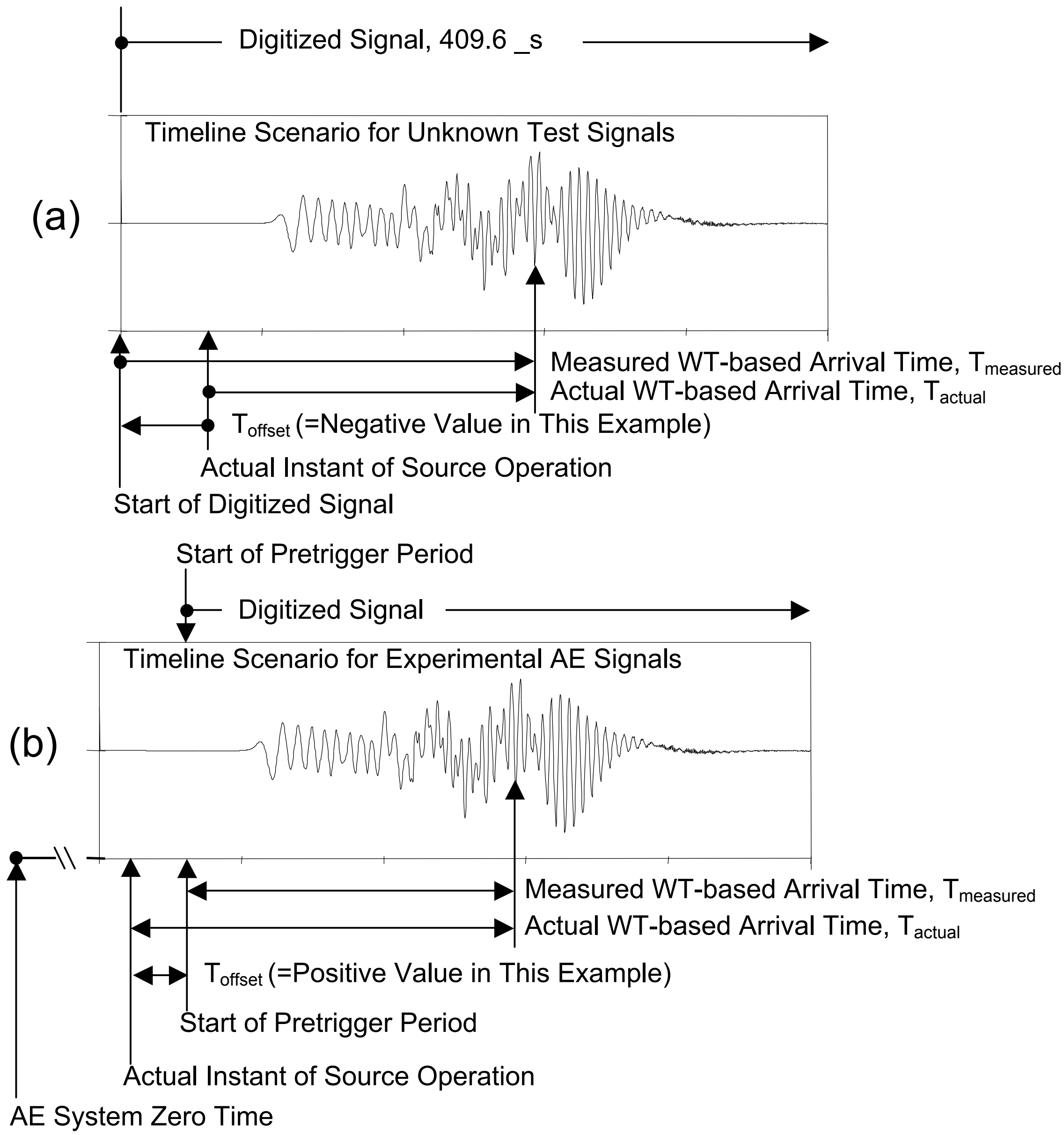

Fig. B-1 Timeline for AE signal: (a) for unknown test signals; (b) for experimental AE signals.

Appendix C: Selected Results for Algorithm Applied to Test Cases

Table C-1 Selected frequency and mode results determined by algorithm for test cases.

Test File Name	Primary Frequency (kHz), Mode	Secondary Frequency, WT Fraction, Mode	Tertiary Frequency, WT Fraction, Mode	Ranges for Known Modes (mm)		
				$R_{60/522}$	$R_{60/270}$	$R_{522/270}$
1	522, S_0	270, 0.48, S_0	60, 0.10, S_0	57	26	59
2	522, S_0	60, 0.77, A_0	270, 0.52, UK*	58	-	-
3	270, S_0	522, 0.85, S_0	60, 0.26, S_0	63	21	66
4	522, S_0	60, 0.44, A_0	270, 0.22, UK	57	-	-
5	60, A_0	522, 0.8, S_0	270, 0.29, UK	59	-	-
6	60, A_0	270, 0.33, A_0	522, 0.18, A_0	117	117	121
7	522, S_0	270, 0.54, S_0	60, 0.12, S_0	119	128	118
8	522, S_0	270, 0.39, S_0	60, 0.08, S_0	179	186	178
9	60, A_0	270, 0.16, UK	522, 0.09, S_0	175	-	-
10	522, S_0	270, 0.58, S_0	60, 0.13, S_0	179	181	179
11	270, S_0	522, 0.52, S_0	60, 0.28, S_0	195	142	198
12	60, A_0	522, 0.76, S_0	270, 0.33, UK	173	-	-
13	522, S_0	60, 0.84, A_0	270, 0.56, UK	59	-	-
14	60, A_0	270, 0.85, A_0	522, 0.60, A_0	54	54	53
15	522, S_0	270, 0.68, S_0	60, 0.15, S_0	58	26	60
16	60, A_0	270, 0.37, A_0	522, 0.10, A_0	58	72	178
17	60, A_0	270, 0.94, A_0	522, 0.71, A_0	106	111	144
18	270, S_0	522, 0.84, A_0	60, 0.35, A_0	2353	929	172
19	270, S_0	60, 0.68, S_0	522, 0.27, S_0	39	486	13
20	60, A_0	522, 0.79, S_0	270, 0.36, UK	88	-	-
21	270, S_0	522, 0.52, S_0	60, 0.28, S_0	195	142	198
22	270, S_0	522, 0.98, S_0	60, 0.92, S_0	176	108	180
23	60, A_0	522, 0.43, S_0	270, 0.26, UK	175	-	-
24	60, A_0	522, 0.46, S_0	270, 0.28, UK	58	-	-
25	60, A_0	522, 0.33, S_0	270, 0.26, UK	117	-	-

*UK = Unknown at this point

Table C-2 Selected range calculation results for test cases.

Test File Name	Range (mm) assuming A_0 mode for 270 kHz		Range (mm) assuming S_0 mode for 270 kHz		Population coefficient of dispersion (all 3 samples)		Range-based mode selection for 270 kHz	Lowest Population Coefficient of dispersion for 3 pairs of computed ranges examined	Best Computed Range (mm)	% Difference of "best computed range" to known range
	$R_{60/270}$	$R_{522/270}$	$R_{60/270}$	$R_{522/270}$	Assume A_0 mode for 270 kHz	Assume S_0 mode for 270 kHz				
1	-	-	-	-	-	-	-	0.016	58	2.6
2	141	84	57	58	0.364	0.007	S_0	0.004	58	3.9
3	-	-	-	-	-	-	-	0.020	64	7.5
4	149	86	61	59	0.394	0.024	S_0	0.014	60	0.2
5	117	77	48	53	0.288	0.083	S_0	0.050	51	15.4
6	-	-	-	-	-	-	-	0.002	117	2.3
7	-	-	-	-	-	-	-	0.002	118	1.5
8	-	-	-	-	-	-	-	0.001	179	0.8
9	174	175	70	119	0.003	0.352	A_0	0.001	175	2.8
10	-	-	-	-	-	-	-	0.000	179	0.6
11	-	-	-	-	-	-	-	0.008	196	9.0
12	461	263	184	179	0.401	0.024	S_0	0.013	181	0.7
13	142	85	58	58	0.364	0.008	S_0	0.004	58	2.9
14	-	-	-	-	-	-	-	0.001	54	9.4
15	-	-	-	-	-	-	-	0.016	59	1.7
16	-	-	-	-	-	-	-	0.112	65	8.1
17	-	-	-	-	-	-	-	0.021	108	9.8
18	-	-	-	-	-	-	-	0.434	1641	2635
19	-	-	-	-	-	-	-	0.514	26	78.3
20	-102	29	-38	20	15.940	2.209	S_0	0.624	54	69.7
21	-	-	-	-	-	-	-	0.008	196	9.0
22	-	-	-	-	-	-	-	0.011	178	1.1
23	185	178	75	121	0.024	0.330	A_0	0.009	176	2.1
24	83	66	35	45	0.153	0.206	A_0	0.064	62	3.0
25	119	118	49	81	0.006	0.340	A_0	0.002	117	2.2

*UK = Unknown at this point