

Comparison of Some Algorithms to Estimate the Low and High State Level of Pulses

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Abstract

The Subcommittee on Pulse Techniques (SCOPT) of the Instrumentation and Measurement Society is developing a new standard for pulse analysis. All of the authors serve on the committee. Former members of SCOPT wrote references [1] to [4]; however, references [1] and [2] are no longer available. Our committee is re-writing references [1] to [4]. Currently we are working on the estimation of the low and high state levels of pulses. Since the waveforms considered contain two states, the terms "low state" and "high state" may be used interchangeably with the terms "state 1" and "state 2," respectively. The estimation of other pulse parameters, such as pulse amplitude, transition duration (rise and fall time), overshoot and undershoot, pulse duration or width, and settling parameters, depend on the estimate of the levels for the low and high states. So, these algorithms are the foundation for the proper estimation of pulse parameters. Some other names for the low and high state levels of pulses are "base magnitude" and "top magnitude" [1, 3], as well as "base-line", "bottom line" and "top-line". References [2] and [4] describe algorithms for estimating the magnitude of the state 1 and state 2 levels that are based on histograms of the pulse waveform. However, the algorithms leave many choices to the user. Due to these user choices, different results can be obtained for the state 1 and state 2 levels that are all compliant with the standard. In this paper, we compare the results of several different algorithms.

1. Background

In this section, we describe the histogram algorithm for determining state levels that appeared in references [2] and [4]. There is no requirement that the same algorithm be used for determining the low and high state levels. Before we describe the histogram method, the three most common intuitive methods for determining the state levels are mentioned which are: (1) initial and final values of the waveforms, (2) minimum and maximum values of the waveform, and (3) averages over intervals at the start and end of the waveform. For completeness, we mention two other methods (1) the user specifies the state levels, and (2) the pulse generator under analysis includes a control to output its static low and high state level voltages. In this last case, the user can measure the state levels with a high accuracy multimeter rather than a waveform recorder.

1.1. Method Described in ANSI/IEEE Std 181-1977[2]

The ANSI/IEEE Std 181-1977 [2] describes the histogram method for determining the low and high state levels of a waveform. A histogram is an amplitude density (or occurrence) representation of a signal (see Sec. 3). For edification, a step-by-step graphical description of the histogram methods follows:

- (1) Assume that a pulse waveform (or a transition waveform) such as that shown in Figure 1a has a superimposed rectangular grid in which each elementary rectangle has length Δt and height Δm .
- (2) Develop the occurrence density histogram by:
 - (a) For each vertical element, of height Δm , count the number of elementary rectangles through which the pulse waveform passes.
 - (b) At the level corresponding to the location of the vertical element, draw a histogram element whose length is proportional to the count. This procedure yields the truncated bimodal histogram shown in Figure 1b that can be divided into two histograms that we shall call H_1 , the low state histogram, and H_2 , the high state histogram, where H_1 contains a peak, P_B , and H_2 contains P_T .
- (3) Consider the histograms H_1 and H_2 separately. Calculate the means or modes of H_1 and H_2 which then become the levels for state 1 and state 2, respectively. A graphical solution yields crude results and is used for describing the generation of the histogram. Actual analysis should be performed with algorithms coded in a computer language. As Δt and Δm become smaller, numerical calculation of the means and modes of H_1 and H_2 become more refined measures of the state levels.

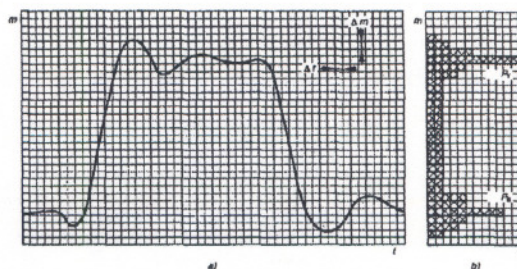


Figure 1. Graphical determination of histogram: (a) Pulse waveform, and (b) Histogram

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Modern instrumentation typically provides a waveform discretized in both amplitude and time. Unless waveform data are generated by interpolation, Δt is fixed by the instrument. Amplitude discretization is determined by several factors (see Sec. 3.1.1) and Δm should not be chosen such that it is smaller than the discretization limit or so large that it compromises the amplitude resolution of the low and high state levels.

1.2. Discussion on the Histogram Method

The above description of the state level algorithm leaves several choices to the user. The first choice for the user is where to split the total histogram into two halves, H_1 and H_2 . After splitting the histogram, the user must choose whether to use the mean or the mode of the histogram in step (3) of Sec. 2.1. According to the standard [2, 4], the mean in step (3) is "best suited for the analysis of pulse waveforms with bases and tops of significant relative duration when the smallest error in the analysis is desired." Similarly, the choice of the mode in step (3) is "best suited to the analysis of pulse waveforms with bases and tops of significant duration when results that are compatible with visual observation and mental analysis by an operator are desired." ("Bases" and "tops" refer to the levels of states 1 and 2.) In addition to choosing the mean or mode of the histogram, the user might also choose to use the median or trimmed mean in step (3) in order to be insensitive to outliers in the waveform. In summary, the user must choose the mean, the mode, the median or some other function of the histogram in step (3).

For numerical methods based on sampled waveforms, Δt is the sample interval and is fixed, and Δm is the bin size of the histogram. The number of bins is initially undetermined and must be specified by the operator. The only guidance to the operator is that as Δm becomes smaller, the measures become more refined. As the number of bins is increased, the estimates of state 1 and state 2 reach a region of steady behavior [5]. Beyond this obvious hint, the algorithms give no guidance for optimally choosing Δm . This leads to some questions. Can adequate results always be obtained for a fixed number of histogram bins? Is the choice of Δm related to the sampling rate, or some parameter that depends on the waveform recorder? The point to be made from this discussion is that the standards specify a collection of algorithms rather than a single one.

2. Histogram Methods

A histogram is an amplitude density representation of a signal, whereas, for comparison, a waveform is an amplitude-versus-time representation of a signal. The amplitude density representation shows the number of occurrences of a given amplitude versus amplitude. To generate a histogram, the amplitude range must be divided into M unique, but not necessarily equal, amplitude intervals. For simplicity, however, we will show a pseudo-code algorithm only for the

equal-amplitude-interval case. The amplitude interval is called the histogram bin width and M is also called the number of bins or the histogram size. The histogram is formed by counting the number of times a waveform value fits within a particular histogram bin.

2.1. Histogram Algorithm

We now describe the histogram algorithm. The choice of the bin boundaries is important. We describe three ways to choose the bins in Section 3.2.

- (1) Find the maximum and minimum amplitude values, A_{\min} and A_{\max} , of the waveform.
- (2) Calculate the waveform amplitude range, A_R , using:

$$A_R = A_{\max} - A_{\min}.$$

- (3) Calculate the bin width, ΔA :

- (a) For equal sized bins, find ΔA by dividing A_R by M (selection of M is discussed in sec. 3.2):

$$\Delta A = \frac{A_R}{M} = \frac{A_{\max} - A_{\min}}{M},$$

- (b) For unequal sized bins, the user specifies an array of bin sizes ΔA_i .

- (4) Sort through the waveform values, S_i , and if the value lies within the range of a bin, that is, for equal sized bins:

$$A_{\min} + (i-1) \cdot \Delta A \leq S_i < A_{\min} + i \cdot \Delta A, \text{ for } 1 \leq i \leq M,$$

or, for unequal sized bins:

$$A_{\min} + \Delta A_i \leq S_i < A_{\min} + \Delta A_{i+1}, \text{ for } 1 \leq i \leq M,$$

then increment the count of the i^{th} histogram bin. The following pseudo-code algorithm is an example of a sort and increment operation.

```

reset histogram to zero ( $B_i = 0$ , for all  $i$ )
 $A_0 = A_{\min}$ 
loop on  $i$ 
   $A_{i+1} = A_i + \Delta A_i$ 
  loop on  $j$ 
    if ( $A_i \leq S_j < A_{i+1}$ ) then  $B_i = B_i + 1$ 
  end  $j$  loop
end  $i$  loop

```

The A_i are the boundaries of the histogram bins, the B_i are the counts, that is, the number of times a waveform value was found between adjacent A_i , the S_i are the waveform values, and the $\Delta A_i = \Delta A$ for equal-sized bin sizes.

2.2. Selection of the number of histogram bins, M

Three methods are described in this section to select M for a waveform that exhibits a bimodal amplitude distribution and contains one transition. The limitations of each method for determining M are indicated. All of these methods are based on the requirement that the extracted pulse parameters agree with observation. The value of M has an upper and lower limit. The value of M should be large enough so that the desired amplitude resolution of the parameters that are

derived from the histogram is not compromised. The value of M should not be so large that the histogram bin width is smaller than the amplitude quantization of the waveform. The amplitude quantization is dependent on the input range of the instrument over which the input range of the analog-to-digital converter (ADC) is applied, the number of bits in the ADC, and whether or not signal averaging was performed.

3.2.1. Method 1 (M1)

Select a fixed value of M . The selection of M may be based on observation, common practice, or some other valid means.

3.2.2 Method 2 (M2)

A large (or small) value of M is selected as an initial value. The value of M is then decremented (or incremented) until a particular histogram criteria is attained. One criteria that has been used is that the least populated of the two mode bins contains a count of at least 10. This method assumes the waveform exhibits a bimodal amplitude distribution, contains a single transition, and that it is positioned such that the bin corresponding to either the state 1 or state 2 levels has a count of at least 10. Typically this latter requirement is assured by positioning the waveform such that the duration of either state 1 or state 2 is no less than 10 % of the waveform epoch. (Although shorter spans may work, this has not been tested.) This method can be adapted to apply to waveforms containing more than one transition and more than two modes in the amplitude distribution if the waveform data is appropriately parsed. However, for each segment, the span of the state 1 or state 2 level in that waveform segment must provide at least 10 amplitude occurrences. If this method is implemented automatically, that is, without operator intervention, it requires that the state 1 and state 2 levels are located in opposite halves of the histogram.

```

generate initial histogram (using maximum value for M)
flag = high
while (flag = high)
    flag = low
    upper_count = 0
    lower_count = 0
    loop on i, 1 ≤ i ≤ M/2
        if (lower_count < Bi) lower_count = Bi
    end i loop
    loop on i, M/2 < i ≤ M
        if (upper_count < Bi) upper_count = Bi
    end i loop
    if (lower_count < 10 or upper_count < 10) then
        M = M/2
        generate histogram
        flag = high
    end if
end while

```

3.2.3 Method 3 (M3)

This method, which is based on reference [5], provides a variable histogram size. The method is based on a region in a pulse-parameter versus M curve that is constant over a range of M . (Reference 5 failed to state that the waveforms used in the study were the result of 1024 averages.) This method assumes the waveform exhibits a bimodal amplitude distribution and contains one transition. However, the method may be expanded to allow for more modes and transitions. The following procedure describes this process.

- (1) Generate the set of test histograms.
 - (a) Determine the upper and lower limits for the number of histogram bins, M_{lo} and M_{hi} . M_{lo} should be chosen so that the desired amplitude resolution is not compromised in the event this number of bins is selected by the algorithm. M_{hi} should be chosen so that the amplitude range of a histogram bin is not smaller than the amplitude quantization. For typical waveform data, it is not necessary to generate a histogram with $M_{hi} > 8192$ or $M_{lo} < 256$.
 - (b) Select the number, K , of histograms to use and compute these K histograms.
 - (2) Select the number, M , of histogram bins for the final histogram.
 - (a) Select a waveform or histogram parameter, P , that is dependent on M . A parameter that works for step-like waveforms and is easy to compute is the pulse amplitude or its rate of change with M , $P(M)$ or $\Delta P(M)$.
 - (b) Calculate the selected parameter, P_i , $1 \leq i \leq K$, from each of the K histograms and generate a parameter vs M array.
 - (c) Define the stability criterion (such as minima, or constant-valued regions) in the parameter vs M data. For $\Delta P(M)$, the extent of a nearly-zero-valued region works well.
 - (d) Find at least one stability region. (Iteration may be required if many regions exist.)
 - (e) Calculate M for the first unique stability region (no overlap with adjacent stability regions).
 - (3) Compute the final histogram (see Section 3.1) using the value of M found in step (2e).

3.3 Mean of Density Distribution

After computing the histogram, the estimates of state 1 and state 2 are computed. Some obvious choices for estimates are the mean, mode, trimmed mean, and median. We describe how to use the mean and mode as estimates. We now turn to an algorithm is based on determinations of the means of the histogram of a single transition waveform or a single pulse waveform.

- (1) Compute histogram as described in Section 3.1 including the choice of the bins via Method 1, 2, or 3.
- (2) Separate the histogram into two parts H_1 and H_2 . Separating the histogram into two parts requires knowing or selecting a waveform level above which can be found P_B and below which can be found P_T . Waveform aberrations and other spurious artifacts may adversely affect the ability of automated algorithms to find the appropriate waveform level. On the other hand, manual (operator) selection of the

appropriate waveform level will generally not be confounded by spurious content.

(3) Consider the histograms H_1 and H_2 separately and calculate the levels of the means of H_1 and H_2 and take the levels of these means as the state 1 and state 2 levels, respectively.

This algorithm is best suited to the analysis of waveforms with state levels of significant relative duration when the highest accuracy is desired.

3.4 Mode of Density Distribution

This algorithm is based on determinations of the modes of the histogram of a single transition waveform or a single pulse waveform and is identical to the previous algorithm (mean of density distribution) except for step (3) of Section 3.3 which is as follows:

(3) Consider the histograms H_1 and H_2 separately and determine the levels of the modes of H_1 and H_2 and take the levels of these modes as the state 1 and state 2 levels, respectively.

This algorithm is best suited to the analysis of waveforms with state levels of significant relative duration when results which are compatible with visual observation and mental analysis by an operator are desired.

3. Results

In this paper, we will compare the three intuitive, non-histogram methods with four histogram methods. Our main goal is to study the dispersion in the estimated state levels caused by the algorithms. Seven algorithms were used to estimate state 1 and state 2 for two series of waveforms, K and S.

The K series of waveforms are shown in Figure 1. The waveform K103 contains a decaying oscillation. The 50% reference level of this waveform is crossed twice. Waveform K103M1 contains an oscillation that decays slower than waveform K103. Waveform K103M2 contains a glitch. Waveform K103M3 contains a runt soon after the transition. Waveform K103M4 contains a runt after the oscillations have noticeably decayed. Waveform K103M5 (not shown in Figure 1) is waveform K103 plus white, normally-distributed noise with $\sigma = 0.01$. The target values for state 1 and state 2 levels for the K series waveforms are 0.0 and 1.495.

The seven algorithms are: A1, which uses a histogram with equal bin sizes (Sec.3.2.1) and the mode; A2, which uses Method 2 (Section 3.2.2) and the mode; A3, which uses Method 3 (see Sec. 3.2.3) and the mode; A4, which is based on Method 1 of Sec. 3.2.1 uses a histogram with unequal bin sizes and the trimmed mean; A5, the initial and final value of the waveform; A6, the minimum and maximum value of the waveform; and A7, the average of the first and last 10 values of the waveform. The histogram methods A1 through A3 are

performed automatically using a computer; they require no operator intervention. The histogram bins in A4 are chosen by the user. From Figure 1, it can be seen that bins are required near 0 and 1.5 for the K series waveforms. For the K series waveforms, the bin boundaries chosen are: -0.01, -0.005, 0, 0.005, 0.01, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3, 1.4, 1.45, 1.46, 1.47, 1.48, 1.49, 1.5, 1.51, 1.52, 1.53, 1.54, and 1.55. Levels for states 1 and 2 are estimated from the mean of the subhistograms H_1 and H_2 . Note that for A4, the user allocated 4 bins for state 1 and 10 bins for state 2. Subhistogram H_1 contains the 4 bins near 0. Subhistogram H_2 contains the 10 bins near 1.5.

Table 1 shows the estimates of state 1 and state 2 for the K series of waveforms. The minimum and maximum algorithm (A6) is obviously a bad choice for these waveforms because the extreme values are significantly larger than the actual state levels. Methods A5 and A7, on the other hand work very well for both the K and S series waveforms. Although not apparent from the waveforms used here, these algorithms would not work if the waveforms contained oscillatory, noisy, or otherwise spurious content near their ends. Algorithms A1 through A3 fail to estimate the level of state 1 for the K series waveforms (K103M2, K103M3 and K103M4) where the maximum amplitude of the waveform is greater than two times the pulse amplitude (target value of 1.495). This failure is a result of the splitting of the histogram (see Sec. 2.1) into two halves which causes the levels for state 1 and state 2 to exist in the same half of the histogram. The error relative in the levels of state 1 and state 2 using A4 are less than 2% of pulse amplitude. A4 uses less than 30 bins to find the state 1 and state 2 levels whereas the other histogram-based methods require thousands of bins. This is not surprising since A4 simply placed 4 bins of size 0.005 around 0. However, A4 requires the operator to manually input the bins.

The S series of waveforms are shown in Figure 2. These waveforms are actual measured waveforms where additional noise or aberrations have been added for the purpose of these tests. The target values for state 1 and state 2 levels for the S series of waveforms are 0.0 and 1.0. For the waveform designated as PT_S2 (not shown), state 2 switches between 0.95 and 1.05.

From Figure 2, it can be seen that bins are required near 0 and 1.0 for the S series waveforms. For the S series, the bin boundaries chosen using M4 are: -0.01, -0.005, 0, 0.005, 0.01, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.91, 0.92, 0.93, 0.94, 0.95, 0.96, 0.97, 0.98, 0.99, 1, 1.01, 1.02, 1.03, 1.04, 1.05, 1.06, 1.07, 1.08, 1.09, and 1.1. Note that the user allocated 4 bins for state 1 and 19 bins for state 2. Subhistogram H_2 contains the 19 bins near 1.5. The choice of the bins was not optimized. Note that the 19 bins of subhistogram H_2 for waveform PT_S2 cover both 0.95 and 1.05. Because the waveform PT_S2's state 2 switches

between 0.95 and 1.05 (switching every fourth element), placing bin boundaries at 0.95 and 1.05 is a poor choice. For noiseless waveforms such as PT_S2, an optimum choice centers a bin on 0.95 and another bin on 1.05.

Table 2 shows the estimates of state 1 and state 2 levels for the S series of waveforms. As with the K series waveforms, A6 fails to properly estimate state 1 or state 2 when undershoot (preshoot) and/or undershoot is present. The other non-histogram methods, A5 and A7, although they provide accurate values for the level of state 1, will be sensitive to spurious content near the ends of the waveforms. Consequently, they should be used with caution. Although none of the methods accurately determine the level for state 1, the errors in the level of state 1 using algorithms A1 through A3 are much less than 1% of amplitude. Similarly, none of the algorithms exactly determined the level of state 2 for all of the S series of waveforms. A3 typically provided levels for state 1 and state 2 closer to the target values than the other histogram methods. However, the accuracy of A1 and A2 already exceeds that for specifications of typical pulse parameter calibrations [6]. When the first 1020 values of waveform PT_S2 were analyzed by methods A2 and A3 with 7636 bins, the state 2 levels changed to 1.05 for A2 and to 1.049863 for A3.

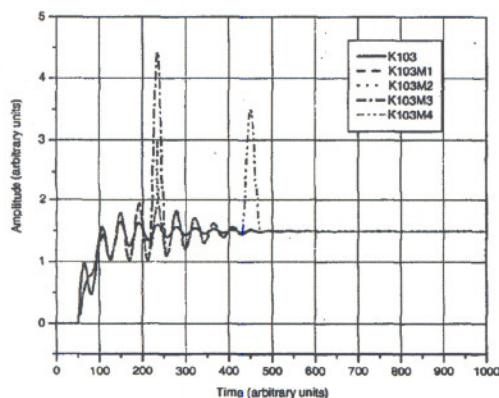


Figure 2. K Series of Waveforms

Acknowledgments

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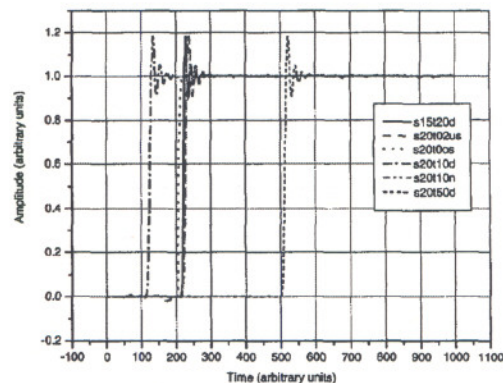


Figure 3. S Series of Waveforms

4. Conclusion

This paper illustrates the use of different algorithms to estimate pulse parameters. The algorithms by which the low and high state levels (bottom-line and top-line) of a waveform are extracted yields different estimates. The low and high state levels of a waveform are required to determine all other pulse parameters (amplitude, transition duration, aberrations, etc.). Consequently, errors and uncertainties in the low and high state levels affect all other pulse parameter estimations. We hope that readers will be motivated to develop better algorithms and submit them to SCOPT for inclusion in the new standard.

5. References

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6. *NIST Calibration Services Users Guide, SP 250*, National Institute of Standards and Technology Special Publication 250, U.S. Government Printing Office, Washington, DC, 1998.

Waveform	State 1	State 2	Bins	Algorithm
K103	0.000000	1.494940	4096	A1
K103	0.000000	1.494900	4096	A2
K103	0.000000	1.494800	7319	A3
K103	-0.002432	1.494985	30	A4
K103	0.000000	1.494937	NA	A5
K103	0.000000	1.657627	NA	A6
K103	0.000000	1.494899	NA	A7
K103M1	0.000000	1.494800	4096	A1
K103M1	0.000000	1.494800	4096	A2
K103M1	0.000000	1.494800	7477	A3
K103M1	-0.001667	1.495887	30	A4
K103M1	0.000000	1.494998	NA	A5
K103M1	0.000000	1.933281	NA	A6
K103M1	0.000000	1.494994	NA	A7
K103M2	1.494870	1.501460	4096	A1
K103M2	1.494100	1.517600	512	A2
K103M2	1.494700	1.561200	1128	A3
K103M2	-0.001667	1.495887	30	A4
K103M2	0.000000	1.494998	NA	A5
K103M2	0.000000	3.000000	NA	A6
K103M2	0.000000	1.494994	NA	A7
K103M3	1.494540	4.395230	4096	A1
K103M3	0.000000	1.484800	128	A2
K103M3	1.494700	4.419400	7239	A3
K103M3	-0.001667	1.495887	30	A4
K103M3	0.000000	1.494998	NA	A5
K103M3	0.000000	4.419968	NA	A6
K103M3	0.000000	1.494994	NA	A7
K103M4	1.494630	1.798850	4096	A1
K103M4	0.000000	1.490400	128	A2
K103M4	1.494900	1.814300	7715	A3
K103M4	-0.001667	1.495486	30	A4
K103M4	0.000000	1.494998	NA	A5
K103M4	0.000000	3.500289	NA	A6
K103M4	0.000000	1.494994	NA	A7
K103M5	0.006290	1.489140	4096	A1
K103M5	-0.011034	1.487077	4096	A2
K103M5	0.006310	1.499049	5255	A3
K103M5	0.008038	1.495410	30	A4
K103M5	0.002872	1.499548	NA	A5
K103M5	-0.024233	1.665266	NA	A6
K103M5	0.002605	1.494493	NA	A7

Table 1. State Estimates of K Series Waveforms from Seven Algorithms,
NA = not applicable

Waveform	State 1	State 2	Bins	Algorithm
pt_s2	0.000000	0.949770	4096	A1
pt_s2	0.000000	0.949768	4096	A2
pt_s2	0.000000	0.949986	7160	A3
pt_s2	-0.002500	0.994897	34	A4
pt_s2	0.000000	0.950000	NA	A5
pt_s2	0.000000	1.050000	NA	A6
pt_s2	0.000000	0.990000	NA	A7
s15t20d	-0.000132	0.999712	4096	A1
s15t20d	-0.000132	0.999712	4096	A2
s15t20d	-0.000029	0.999914	7319	A3
s15t20d	-0.001019	0.996184	34	A4
s15t20d	0.000000	0.999000	NA	A5
s15t20d	-0.001000	1.184000	NA	A6
s15t20d	0.000000	0.999900	NA	A7
s20t02us	-0.000266	0.999786	4096	A1
s20t02us	-0.000266	0.999786	4096	A2
s20t02us	-0.000042	0.999938	6684	A3
s20t02us	-0.001466	0.995863	34	A4
s20t02us	0.000000	1.000000	NA	A5
s20t02us	-0.022000	1.181000	NA	A6
s20t02us	0.000000	1.000000	NA	A7
s20t0os	-0.000021	0.999777	4096	A1
s20t0os	-0.000021	0.999777	4096	A2
s20t0os	-0.000056	0.999898	6366	A3
s20t0os	-0.002132	0.995729	34	A4
s20t0os	0.000000	1.000000	NA	A5
s20t0os	-0.001000	1.001000	NA	A6
s20t0os	0.000000	1.000200	NA	A7
s20t10d	0.000000	0.999946	4096	A1
s20t10d	0.000000	0.999946	4096	A2
s20t10d	0.000000	0.999922	7398	A3
s20t10d	0.000470	0.998106	34	A4
s20t10d	0.000000	1.000000	NA	A5
s20t10d	0.000000	1.180000	NA	A6
s20t10d	0.000000	1.000000	NA	A7
s20t10n	-0.000185	0.999779	4096	A1
s20t10n	-0.000185	0.999779	4096	A2
s20t10n	-0.000169	0.999975	6128	A3
s20t10n	0.000898	0.999600	34	A4
s20t10n	0.000000	0.996000	NA	A5
s20t10n	-0.006000	1.185000	NA	A6
s20t10n	0.000000	0.997500	NA	A7
s20t50d	-0.000135	0.999794	4096	A1
s20t50d	-0.000135	0.999794	4096	A2
s20t50d	-0.000013	0.999960	6763	A3
s20t50d	-0.001644	0.996271	34	A4
s20t50d	0.000000	1.000000	NA	A5
s20t50d	-0.001000	1.180000	NA	A6
s20t50d	0.000000	1.000000	NA	A7

Table 2. State Estimates of S Series Waveforms from Seven Algorithms,
NA = not applicable