Firmware Measurement Algorithms for the HP 83480 Digital Communications Analyzer

Parametric measurements measure waveform properties such as rise time, fall time, overshoot, period, and amplitude on either a pulse waveform or an eye diagram. Mask measurements compare the shape of the waveform to a predefined mask. Eye parameter measurements measure properties that are unique to eye diagrams, such as eye height, eye width, jitter, crossing height, and extinction ratio.

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An important part of the HP 83480 digital communications analyzer is its extensive set of built-in measurements designed especially for telecommunications applications. Internal firmware algorithms permit the user to quickly measure waveform properties that would be tedious and error-prone to measure manually. The algorithms also eliminate the subjectiveness inherent in a manual measurement. Of course, any built-in measurement is only as accurate as its firmware algorithm. A major objective for this instrument's design team was to develop robust algorithms capable of producing reliable results in virtually all situations.

The HP 83480's built-in measurements fall into three general categories:

- Parametric measurements measure waveform properties such as rise time, fall time, overshoot, period, and amplitude on either a pulse waveform or an eye diagram.
- Mask measurements compare the shape of the waveform to a predefined mask. If any part of the waveform intrudes into the mask, it is counted as a failure.
- Eye parameter measurements measure properties that are unique to eye diagrams, such as eye height, eye width, jitter, crossing height, and extinction ratio.

Parametric measurements can be made in either a real-time mode or a statistical mode. In the real-time mode the measurement is performed immediately on each acquired waveform. In the statistical mode, histograms are used to perform the measurement on a database representing multiple waveform acquisitions. Mask and eye parameter measurements are inherently statistical parameters and so are only measured using histograms.

Design Leverage

As much as possible, the firmware design of the HP 83480 was leveraged from existing code for the HP 54720 digitizing oscilloscope. The HP 54720 incorporated an extensive set of very accurate pulse parameter measurements together with basic mask test capabilities. The parametric measurements did not function on eye diagrams, however, so this capability needed to be added. A number of additional eye parameter measurements were developed, and the existing mask test capability was extensively upgraded to include such features as a full set of standard telecom masks, built-in mask margins, and fixed voltage masks.

An important feature of these measurements is that they operate in real time, automatically updating on every acquisition of the waveform. Before the HP 54720, HP high-speed oscilloscopes made measurements in a single-shot mode. When the user pushed the button to determine rise time, for instance, the oscilloscope stopped acquiring data and made the measurement on a frozen waveform display. The real-time measurement mode was considered much more convenient, but it increased the complexity of the algorithm design. Not only did the algorithms need to be accurate, they also had to be fast enough not to slow down instrument operation perceptibly.

Parametric Measurements

From the outset, the design team wanted the parametric measurements to operate correctly on both pulse waveforms and eye diagrams. This proved to be a challenge in several ways. First, while the IEEE has developed standard definitions for such parameters as rise time, fall time, and overshoot for simple pulse waveforms, no similar standards exist for eye diagrams. To develop the appropriate definitions, team members spent many hours in discussions with potential users to understand their needs. Alternative algorithms were extensively tested to determine those that best met expectations.
A second challenge arose because of the different signal coding formats used on the various electrical tributary rates. For example, certain low-bit-rate transmission formats use a bipolar coding scheme known as alternate mark inversion (AMI). In this format, each successive logical one bit is represented by a pulse of polarity opposite to that of the previous pulse. In the case of a DS-1 signal at 1.544 Mbits/s, for instance, the amplitude of the first logic 1 pulse is specified as +3.0V while the amplitude of the next is −3.0V. Subsequent logic one pulses alternate between these two levels. The algorithm for measuring rise time on an AMI pulse waveform had to be versatile enough to produce the correct result whether the onscreen display was set to show only a single positive-going pulse or both positive-going and negative-going pulses (Fig. 1).

![Fig. 1](image)

*Fig. 1.* The HP 83480 measurement algorithms are designed to operate correctly on alternate mark inversion (AMI) waveforms regardless of whether the display shows both positive and negative pulses (a) or only a positive pulse (b).

### Histograms and Color-Graded Displays

Since eye diagrams are essentially a statistical representation of all possible one-zero waveform combinations, it makes sense to measure their waveform properties statistically. To do this, powerful database and histogram capabilities were developed, and these became the foundation for the new measurements.

The database in the HP 83480 corresponds to the size of the display—451 columns by 256 rows. Every waveform regardless of record length or number of vertical bits is mapped onto this database structure. Behind each database location, or pixel, is a 16-bit counter. Each time a waveform strikes a particular pixel, it is recorded as a “hit” at that location and the counter for that pixel is incremented by one. Up to 65535 hits can be counted at each pixel (Fig. 2).

To give the user an easy visual indication of the distribution of data in the database, the instrument uses a color-graded display mode. This mode maps the database into seven display colors, with each color representing a specific range of database hits. The algorithm that determines the range of hits corresponding to each color was carefully chosen to provide a meaningful display regardless of the maximum number of hits in the database. This display provides a very powerful three-dimensional view of the eye diagram (Fig. 3). It clearly shows the most prevalent paths of the signal as well as spurious noise and jitter.

Histogram measurements are derived directly from the database. A histogram window is set up to select a range of rows and columns to be included in the histogram as shown in Fig. 4. A vertical histogram is computed by windowing across a slice of time and plotting the frequency of occurrence for each database row. A horizontal histogram is computed by windowing across a range of voltages and plotting the frequency of occurrence for each database column.

The HP 83480 can display the histogram with either a linear or a logarithmic scale. With the linear scale, the histogram is plotted in hits per division. With the logarithmic scale, the histogram is plotted in dB per division. For each pixel, the displayed value is found from:

\[
\text{dB} = 20 \log_{10} \frac{N}{P},
\]

where dB is the displayed value for the pixel in dB, N is the number of hits in the pixel, and P is the peak number of hits within the histogram window.

The linear scale is useful for looking at the peak and distribution of the histogram. The logarithmic scale is useful for observing the tails of the histogram.

In addition to the pictorial representation of the histogram, the HP 83480 computes a series of parametric measurements on the histogram data. The width of the histogram, the average value, the standard deviation, and the mean value plus and
Waveforms are mapped onto a database for statistical analysis. The database consists of 115,456 pixels arranged in 451 columns by 256 rows. Each pixel can record up to 65,535 waveform hits.

The color-graded display mode provides a visual representation of the waveform distribution.

minus one, two, and three standard deviations are all useful parameters for understanding the noise and jitter of an eye diagram.

**Eye Parameter Measurements**

Measurements of eye parameters are made by automatically constructing histograms over selected regions of the database while in the color-graded display mode. Although these measurements could technically be made without activating the color-graded display mode, the design team decided that this was the best way to ensure that what the user sees on screen is correlated with the data in the database.

The measurement algorithms construct vertical and horizontal histograms to search for reference features in eye diagrams. Most eye parameters are referenced to four fundamental properties of the eye diagram:

- Top level, $V_{top}$, is the mean logic one level.
Fig. 4. Histograms are used to analyze waveform statistics. In this example, a vertical histogram has been constructed in a rectangular window inside the X1-X2, Y1-Y2 markers to determine the mean logic one level of the pulse.

- **Base level**, $V_{\text{base}}$, is the mean logic zero level.
- **Eye crossing** refers to the start of the bit period. By convention, this is defined as the point in time where the rising and falling edges of the eye intersect. Crossing time is defined as $t_{\text{crossing}}$, and crossing amplitude is $V_{\text{crossing}}$.
- **Threshold crossings** are defined as the times at which the signal crosses predefined threshold levels while making the transition between logic levels. Typical threshold levels used on an optical eye diagram are 20%, 50%, and 80% of amplitude.

The algorithms for finding these values have been designed to accommodate a wide range of eye diagram shapes. $V_{\text{top}}$ and $V_{\text{base}}$, for example, are determined by first finding the peaks of a vertical histogram constructed across the database as shown in Fig. 5. $V_{\text{top}}$ is the mean value of the upper peak and $V_{\text{base}}$ is the mean value of the lower peak. The standard deviations of these values are the rms noise levels on the logic one and logic zero levels.

Fig. 5. Vertical histograms are used to find the mean logic one and logic zero levels. In this example, the histogram extends the full width of the eye.

Eye crossing times are located using an iterative algorithm on a horizontal histogram. The initial histogram is constructed on a window that just excludes the $V_{\text{top}}$ and $V_{\text{base}}$ data as shown in Fig. 6. Peaks in this histogram indicate the approximate locations of eye crossings. To find the crossings more precisely, a subsequent histogram is constructed in a narrow window about the approximate crossing point amplitude. The mean value is the crossing time, $t_{\text{crossing}}$, and the standard deviation, $\sigma_{\text{crossing}}$, is the rms jitter. Crossing amplitude is found by taking a vertical histogram on the same window.
Fig. 6. Horizontal histograms are used to find the eye crossing times. The window is set to exclude the logic one and zero level data.

Rise time, fall time, overshoot, and duty cycle distortion measurements depend on finding rising and falling edges on the eye diagram. The HP 83480 finds threshold crossings by forming horizontal histograms using narrow windows centered at each threshold level.

More complex eye parameters are calculated from a set of constituent measurements, which in turn may have their own dependencies. An ordered list of measurements is performed by tracing dependencies using a technique first developed for the HP 54720. The equations for eye parameter measurements are as follows:

- **Eye Height:**
  \( (V_{\text{top}} - 3\sigma_{\text{top}}) - (V_{\text{base}} + 3\sigma_{\text{base}}) \)

- **Eye Width:**
  \( (t_{\text{crossing2}} - 3\sigma_{\text{crossing}}) - (t_{\text{crossing1}} + 3\sigma_{\text{crossing}}) \)

- **Q Factor:**
  \( \frac{(V_{\text{top}} - V_{\text{base}})}{(\sigma_{\text{top}} + \sigma_{\text{base}})} \)

- **Jitter (rms):**
  \( \sigma_{\text{crossing}} \)

- **Jitter (peak-to-peak):**
  \( 6\sigma_{\text{crossing}} \)

- **Crossing Level:**
  \( \frac{(V_{\text{crossing}} - V_{\text{base}})}{(V_{\text{top}} - V_{\text{base}})} \times 100\% \)

- **Duty Cycle Distortion:**
  \( \frac{|t_{\text{rising50\%}} - t_{\text{falling50\%}}|}{(t_{\text{crossing2}} - t_{\text{crossing1}})} \times 100\% \)

- **Overshoot:**
  \( \frac{(V_{\text{top}} + V_{95})}{(V_{\text{top}} - V_{\text{base}})} \times 100\% \)

In the above equations, \( \sigma_{\text{top}} \) is the standard deviation of \( V_{\text{top}} \), \( \sigma_{\text{base}} \) is the standard deviation of \( V_{\text{base}} \), \( \sigma_{\text{crossing}} \) is the standard deviation of \( t_{\text{crossing}} \), \( t_{\text{rising50\%}} \) is the time at which the rising edge reaches the 50% point between \( V_{\text{top}} \) and \( V_{\text{base}} \), \( t_{\text{falling50\%}} \) is the time at which the falling edge reaches the 50% point between \( V_{\text{top}} \) and \( V_{\text{base}} \), and \( V_{95} \) is the amplitude of the 95th percentile of the data in a vertical histogram whose lower bound is \( V_{\text{top}} \) and whose upper bound is the top of the screen.

The user can control several measurement factors: the eye window over which \( V_{\text{top}} \) and \( V_{\text{base}} \) are measured, the signal type of the eye pattern, and the percentile for voltage thresholds. The industry has not yet adopted a consensus for how to measure \( V_{\text{top}} \) and \( V_{\text{base}} \). Some users want the histogram window to extend across the full bit interval while others prefer only a narrow window about the center of the eye where the logic levels have settled to steady state (Fig. 7). With the HP 83480...
the user can window on any time interval from 0 to 100% of the eye. The default window is ±10% around the center of the eye.

Fig. 7. Mean one and zero levels on the same data as in Fig. 5 but found by windowing on only a narrow region about the center of the eye. Notice the difference in the logic one histogram compared to Fig. 5.

The HP 83480 can measure parameters on three different signal types. Optical signals use a simple binary code called nonreturn-to-zero, or NRZ. With this code, the light is turned on for the full duration of a logic one pulse and turned off (or nearly off) for the full duration of a logic zero pulse. Electrical telecommunication signals use two different coding formats. Alternate mark inversion, or AMI, is a three-level format in which a logic zero is represented by a zero-volt signal and logic one pulses alternate between positive-going and negative-going voltages. Coded mark inversion, or CMI, is a binary signal in which a logic 0 includes a transition at the center of the bit period while the logic 1 does not. The HP 83480 can measure waveform parameters on all three signal types as well as unencoded periodic waveforms. Eye parameter measurements such as eye height, eye width, and extinction ratio are performed only on NRZ signals.

The threshold values used for characterizing rising and falling edges can be defined by the user. Rise times of electrical signals are traditionally measured from the 10% amplitude point to the 90% amplitude point. On optical signals, these points are often obscured in the noise, so 20%-to-80% thresholds are frequently used. The HP 83480 can use these or any other user-specified threshold values. Thresholds can also be defined as explicit voltage or power levels.

**Extinction Ratio**

Extinction ratio is a critical parameter for laser transmitters because it is a measure of the signal-to-noise level of the system. It is defined as the ratio of the logic one level amplitude (V_{top}) to the logic zero level amplitude (V_{base}). Although conceptually simple, both hardware and software considerations make the extinction ratio difficult to measure accurately. The impact of hardware design is described in Article 3. The most important software consideration is the removal of dc offset.

A principal source of dc offset comes from the optical-to-electrical (O/E) converter at the vertical channel input. Internal oscilloscope offsets can also play a role. While the HP 83480 has been designed to minimize these offsets, it is not possible to eliminate them completely. To correct for any residual offset, the HP 83480 requires an initial offset calibration. The user first removes the signal input from the optical channel, then pushes the Offset Cal softkey. The HP 83480 automatically measures and stores the offset, V_{offset}, by taking the mean of a large number of samples. Normally, once this calibration is done, it need not be repeated for the rest of the day unless the instrument's temperature changes by more than about five degrees. The HP 83480 allows extinction ratio results to be displayed in one of three formats:

- **dB:** \(10 \log\left(\frac{V_{top} - V_{offset}}{V_{base} - V_{offset}}\right)\)
- **Ratio:** \(\frac{V_{top} - V_{offset}}{V_{base} - V_{offset}}\)
- **Percent:** \(\frac{(V_{base} - V_{offset})}{(V_{top} - V_{offset})} \times 100\).

**Extinction Ratio Frequency Response Correction**

Extinction ratio measurement accuracy can be heavily influenced by the hardware design of the vertical channel. One potentially serious source of error is the frequency response flatness of the channel. To measure extinction ratio accurately, the ac gain and the dc gain of the channel must be identical. A low-frequency gain increase of even 0.5 dB can lead to a large measurement error.

This is a very challenging design objective and is a major reason why the HP 83485A plug-in module (see Article 3) employs a nonamplified optical channel. However, some users need to measure lasers operating at wavelengths or fiber diameters for which HP does not presently provide a solution. Other users need additional sensitivity to measure extremely low-level signals. In these cases an external O/E converter having a nonideal frequency response may have to be used.
Recent research has shown that it is possible to correct in software for frequency response errors in hardware. The HP 83480 provides the ability to enter an extinction ratio frequency response correction factor. To determine this correction factor a signal with known extinction ratio is applied to the O/E converter's input and the measured extinction ratio is recorded. When both extinction ratios—known and measured—are expressed in percent, the frequency response error is a constant, independent of the actual extinction ratio. The value of this constant (in percent) can be entered into the instrument, which then automatically corrects the reading. Once entered, the correction factor is in effect regardless of whether the extinction ratio is displayed in percent, in dB, or as a ratio. With care, measurement accuracy of better than 1% is possible when using this technique.

While the use of frequency response correction considerably improves the measurement accuracy when using a nonideal O/E converter, it is not a universal solution. In general, the correction factor differs depending on the data rate, so a single number is only appropriate at the data rate for which it was determined. Depending on the frequency response characteristics of the external O/E converter, the correction factor can show slight sensitivity to varying data pattern characteristics even at a single data rate.

**Mask Measurements**

Mask tests are often used in production environments as an alternative to eye parameter analysis. By comparing an eye diagram against a predefined mask, the overall quality of the waveform can be assessed in one quick measurement. A mask consists of two parts, as shown in Fig. 8:

- A set of regions, or polygons, on the oscilloscope screen that define keep-out areas for the waveform. Waveforms that intrude into these polygons are counted as mask violations.
- Definitions of the time and amplitude scales for the mask. Many masks use an amplitude scale that is defined relative to the mean one and zero levels of the eye. Others require fixed voltage levels independent of measured signal levels.

![Fig. 8. Concept of mask testing.](image)

The earliest masks were simply drawn on the oscilloscope screen with a grease pencil. Later oscilloscopes included rudimentary built-in mask drawing features. A limitation of these instruments was that the masks were drawn in screen coordinates that did not relate to the scale of the waveform. As the user adjusted the horizontal or vertical scales the mask remained fixed on the screen.

The mask measurement capabilities of the HP 83480 are far more powerful than in any previous instrument. The mask is referenced to true time and amplitude coordinates so that as the user changes the oscilloscope settings, the mask follows the waveform. It is also easy to rescale the mask for different data rates or amplitude levels.

There are two ways to create masks. A large number of standard telecommunications masks are built into the instrument (see Table 1). These masks can be called onto the screen with the touch of a button. For nonstandard needs, the user can create custom masks.
Table I
Standard Masks in the HP 83480 Digital Communications Analyzer

<table>
<thead>
<tr>
<th>Optical</th>
<th>Electrical</th>
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<tbody>
<tr>
<td>OC-1</td>
<td>STS-1 pulse</td>
</tr>
<tr>
<td>OC-3/STM-1</td>
<td>STS-1 eye</td>
</tr>
<tr>
<td>OC-12/STM-4</td>
<td>STS-3 pulse 0, 1</td>
</tr>
<tr>
<td>OC-24</td>
<td>STS-3 eye</td>
</tr>
<tr>
<td>OC-48/STM-16</td>
<td>DS-1</td>
</tr>
<tr>
<td>FC-133</td>
<td>DS-1C</td>
</tr>
<tr>
<td>FC-266</td>
<td>DS-2</td>
</tr>
<tr>
<td>FC-531</td>
<td>DS-3</td>
</tr>
<tr>
<td>FC-1063</td>
<td>PDH 2.048</td>
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<tr>
<td>FDDI</td>
<td>PDH 8.448</td>
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<tr>
<td></td>
<td>PDH 34.4</td>
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<td></td>
<td>PDH 139.25</td>
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</tbody>
</table>

Custom Masks
Up to eight polygons can be created using the display as a drawing pad and the knob to control the vertical and horizontal coordinate of each polygon point. All polygon coordinates are normalized to the dimensions of the eye diagram. For example, (0,0) represents the zero level of the first crossing and (1,1) represents the one level of the second crossing. Special values are also used for the vertical axis minimum and maximum to represent the bottom and top of the screen regardless of the vertical scale. Absolute time and amplitude scales are defined separately from the relative coordinate system.

This coordinate system permits the entire mask definition to be compressed or expanded in either axis by assigning new amplitude or time values to the (0,0) and (1,1) coordinates. It also ensures that the mask tracks the signal when the time base or amplitude settings are modified.

Mask Margins
In a manufacturing environment it is often desirable to add a test line margin to industry-standard masks. At other times it is useful to reduce the size of the mask to determine by how much a waveform fails the test. The mask margin capability of the HP 83480 makes these tasks easy. This feature allows minimum and maximum margin limits to be defined as separate masks around the standard mask. The margin mask can be set as any percentage from -100% under to +100% over the standard mask (Fig. 9). Minimum and maximum mask margins are included in the definitions of the standard masks.

Fig. 9. Mask margins are used to add guardbands for production testing. In this example a 40% margin has been added to an industry-standard OC-12 mask at 622.08 Mbits/s.
Mask Alignment

Before a mask test is conducted, the mask must be properly aligned to the waveform. The HP 83480 provides two methods of automatic alignment. In the first, known as mask-to-waveform alignment, the mask is aligned directly to the displayed waveform and the instrument settings are left unchanged. When this mode is initiated the firmware measures reference points on the eye diagram and positions the mask to align it to the data.

The second alignment method is known as the fill display mode. In this method, the instrument scale settings are automatically adjusted to center one full eye diagram on the screen regardless of initial settings. Fill display makes the most efficient use of the data and so provides the most accurate test results. The mask-to-waveform mode, however, produces much faster results.

Most standard masks are defined with amplitudes relative to the signal amplitude. These masks automatically rescale to fit signals with different amplitudes. However, a few masks are defined using explicit voltage levels. For these fixed-voltage templates the instrument automatically aligns the time position of the mask but maintains a fixed vertical scale as defined in the standard.

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References