Errata

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HP References in this Application Note

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Application Note 343-4

Measuring demodulator image rejection using the HP 8980A Vector Analyzer

This note describes how to measure the image rejection of a vector demodulator. Measuring image rejection is especially important for radar receivers which can mistake image frequencies for targets. Vector modulation and demodulation has been used in radar and communications for many years. As technology has progressed, systems using vector techniques have been pushed to higher and higher levels of performance. Higher performance means an increased need to measure and control imperfections in the various elements of the system. Until now, designers and manufacturers of radar and communications equipment have been forced to use a variety of test methods to measure system performance, often having to build their own specialized test equipment.

Hewlett-Packard has opened a new window for understanding and analyzing vector signals. The HP 8980A Vector Analyzer is a powerful and versatile tool for the analysis of I/Q (vector) modulation. Its marker capabilities greatly simplify many common measurements.

This application note will describe the two tone method for calibrating a demodulator using the HP 8980A. A simple manual technique will be described to measure these imperfections followed by an automated method which extends the dynamic range of the measurement.

A Little Groundwork

The circuit shown in Figure 1 is a common device in many radar and communications applications. It is called a quadrature detector, coherent detector, vector demodulator and many other names. It demodulates a signal into its in-phase (I) and quadrature-phase (Q) components for baseband analysis. An actual circuit can have many errors, but for this note we will deal with only three of these (DC offset, gain imbalance and quadrature error). The effects of nonlinearities, such as harmonics, will be neglected.

Image rejection is a measure of demodulator performance. Also known as the Doppler Image Rejection, it is a measure of the balance between the two channels of a demodulator. Given gain imbalance and quadrature error, we can calculate image rejection (IR):

\[
IR = 10 \log \left\{ \frac{1 + k^2 + 2k \cos(\phi)}{1 + k^2 - 2k \cos(\phi)} \right\}
\]

where \( k \) is the gain imbalance (Q/I) and \( \phi \) is the quadrature error of the demodulator. (This relationship is plotted in Figure 2.)

This application note will, therefore, show how the HP 8980A can be used to measure DC offsets, \( k \) and \( \phi \) and from this calculate image rejection.

Figure 1. Vector Demodulator

Figure 2. Image rejection.
The Two-Tone Technique

Figure 3 shows the setup for the two tone calibration technique. Because the reference and the input are offset in frequency, the quadrature error and gain imbalance manifest themselves at the I and Q channels as shown. The problem lies in accurately measuring the outputs and extracting the desired information. This measurement is often made by directly digitizing the information on the two channels of the demodulator and calculating a complex FFT to find the image rejection.

The FFT approach measures the image rejection within the accuracy limits of the digitizer. The HP 8980A could serve well as this digitizer with its twelve bits of resolution. However, the FFT approach does not reveal the source of the image. The vector analyzer can measure the sources of the degraded image rejection directly. It can determine if the problem is due to quadrature error or gain imbalance. This greatly simplifies adjustment for optimum performance. In addition, the system can be probed at various points in the baseband circuit. This allows fault isolation. The HP 8983A allows tremendous flexibility in making measurements thus speeding test and design time.

The Manual Technique

The HP 8980A Vector Analyzer provides an easy to use, accurate way to observe and measure the output of a demodulator. The manual procedure, for example, can determine the gain and phase offsets necessary to calculate the image rejection of the demodulator.

1) Connect the I channel from the demodulator to the I input of the analyzer and the Q channel to the Q input as shown in Figure 3.

2) Select the I display, and adjust the time per division such that exactly one cycle appears on the screen as shown in Figure 4.

3) Select the Vector display, and adjust the I & Q gain such that the circle (ellipse) is about full scale as shown in Figure 5.

4) Cancel any DC offsets by removing the input signal from the demodulator and adjusting the offset I and offset Q in the GAIN & OFFSET menu until the dot is centered screen as shown in Figure 6.

5) Reconnect the input to the demodulator.
6) Measure the quadrature error by adjusting the Delay 1 in the TIMING menu until the ellipse closes and becomes a straight line as shown in Figure 7. Quadrature error can be derived from the following equation:

\[ \phi = \left( \frac{\text{Delay} \cdot 360}{(10 \cdot \text{Timebase})} \right) - 90^\circ \]

\[ = \left[ \frac{247 \cdot 360}{(10 \cdot 100.2)} \right] - 90^\circ = -1.26^\circ \]

**Figure 7. Measure quadrature.**

7) Measure the gain imbalance by adjusting the \( \Delta I \) and \( \Delta Q \) markers to the peak excursions of the waveform as shown in Figure 8.

Gain Imbalance \( k = \frac{\Delta Q}{\Delta I} = 95.34 \)

\[ 95.54 \]

\[ = 0.998 \]

**Figure 8. Measure gain imbalance.**

8) To correct for any gain error (typically \(< 0.5\%\)) or phase offset (typically \(< 0.72^\circ\)) in the vector analyzer, swap the inputs to the analyzer and repeat the measurement starting at step 4.

9) With the factors \( k_1 \) and \( \phi_2 \) from the first measurement and \( k_1 \) and \( \phi_2 \) from the second, determine the resultant \( k \) and \( \phi \) due to the demodulator:

\[ k = \sqrt{\frac{k_1}{k_2}} \]

\[ \phi = \frac{\phi_1 - \phi_2}{2} \]

10) Calculate the image rejection:
Taking into account the accuracy and noise of the HP 8980A, image rejection as great as 40dB can be measured using the manual procedure. Some systems, however, may require higher performance than this. Using a controller to average out the effects of system noise, the dynamic range of this measurement can be improved.

**Figure 9. Improvements in dynamic range.**

The Automatic Method

The procedure and algorithm for the automatic method of demodulator calibration is included in the Appendix along with the program listing and sample output. The user should average enough to allow sufficient signal to noise ratio in their measurement. Averaging will increase the dynamic range. Figure 9 shows the improvement in dynamic range of the analyzer as a function of the number of averages taken. For example, if the gain imbalance of the device under test is about 1.01 then Figure 2 shows that the image rejection can be as good as 45 db. Therefore, the dynamic range of the measurement should be made at least 55 db. This corresponds to 5 averages as shown in Figure 9. Figure 9 also shows the effect of different gain settings on the dynamic range. For more information on this see Product Note 8980A-2 “Dynamic Range Considerations of the HP 8980A Vector Analyzer”.

**Figure 9. Improvements in dynamic range.**
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Appendix
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Accuracy
The accuracy of the technique used is based on the ability of the program to cancel any gain or phase error introduced by the analyzer. The program is able to measure gain offsets to better than 0.1%. The accuracy with which quadrature error is measured improves with lower quadrature error. This is a consequence of the algorithm used. Because of this, a 4 degree quadrature error is measured with about 1.2% accuracy while a 1 degree quadrature error is measured with 0.3% accuracy. This relationship can be expressed as:

\[ \phi = (0.17 \cdot \tan(\phi)) \cdot 100\% \]

more sensitive to gain imbalance k than quadrature error \( \phi \). While the accuracy curves do curve up and to the right slightly, it is safe to consider them straight as shown in Figure 10.

Summary
Vector demodulators used in radar and communications applications can now be easily calibrated using the HP 8980A Vector Analyzer. The analyzer measures DC offsets, signal magnitudes, quadrature error and gain imbalance. This information is invaluable to quickly adjust systems or verify performance. The analyzer will, also, isolate faults in a vector demodulator allowing adjustment.

![Figure 10. Accuracy of automated method.](image)

![Figure 11. Speed of automatic method.](image)
Appendix: Automatic Demodulator Calibration

Procedure
1) Connect the demodulator to the analyzer as shown in Figure 3.
2) Delay I and Q equally one cycle and adjust the TIME/DIV such that exactly one cycle occupies the 10 divisions of the screen. This could easily be automated for specific test requirements.
3) Run the program and swap the inputs when prompted.

Algorithm
The program performs the following functions:
- Gather trace data
- Measure offsets, magnitudes, gain imbalance and quadrature error
- Cancel analyzer offsets
- Calculate image rejection
1) As the name implies, the Gather...data subprogram gathers the trace information from the analyzer. It averages the number of traces specified by the Num_sweeps variable. It then translates this trace data into volts.
2) The Impairments subprogram measures the offsets, peak-to-peak magnitudes, gain imbalance and quadrature error of the demodulator.
   a. Offsets are simply the average value of the trace on each channel.
   b. The peak-to-peak magnitude of each channel is calculated in the Calc_mag subprogram. The program searches each trace for its maximum and minimum. It then averages the five adjacent points to reduce any effect of noise.
   c. Gain imbalance k is the ratio of the magnitudes of the two channels.
   d. Quadrature error is calculated using the following formula:

\[ \phi = \left( \frac{180}{\pi} \right) \cdot \sin^{-1} \left( \frac{2}{NA_1A_Q} \cdot \Sigma I_iQ_i \right) \]

where \( A_1 \) and \( A_Q \) are the peak values of the I and Q channels and \( I_i \) and \( Q_i \) are the values of the I and Q channels at time \( t \).
3) These measurements are made again with the input swapped, and any offsets due to the analyzer are canceled.
4) The image rejection is calculated and the results printed by the Dsp_results subprogram.

Sample Output

<table>
<thead>
<tr>
<th>CHANNEL OFFSET</th>
<th>MAGNITUDE</th>
<th>QUAD ERROR (PHI)</th>
<th>GAIN IMBALANCE (K)</th>
<th>IMAGE REJECTION (IR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Channel Offset</td>
<td>40 mV</td>
<td>905 Vpp</td>
<td>-1.200 degs</td>
<td>+1.020 dB</td>
</tr>
</tbody>
</table>
Program Listing

```
10  NUM_SWEEPS=3  ! SEE FIGURE 9
20  HSTOP=709
30  DIM 1(0:1023),Q(0:2048)
40  DISP ** PRESS CONTINUE WHEN YOU ARE READY TO START **
50  PRINT
60  CALL Gather_data(HSTOP,NUM_SWEEPS,1,0,0)
70  CALL Impairments(1,0,0,0,0,1,0,0,0,0,0,0)
80  END
90  PRINT

100  ! SEE PROGRAM DESCRIPTION
110  DISP ** SNAP THE 1 AND 0 CHANNELS AND THEN PRESS CONTINUE **
120  PAUSE
130  CALL Gather_data(HSTOP,NUM_SWEEPS,1,0,0)
140  CALL Impairments(1,0,0,0,0,1,0,0,0,0,0,0)
150  ! CALCULATE IMPERFEC TIONS DUE, SOLELY, TO THE MODULATOR
160  K=0.5
170  PH1=PH1+PH1/2
180  L=0.1+1.1*0.2/2
190  O=0.1+1.1*0.2/2
200  Q=0.1+1.1*0.2/2
210  CALL Disp_result1(1.0,0.1,0.1,0.1,0.1,0.1)
220  STOP
230  END

! SUB PROGRAMS

280  CALL Gather_data(HSTOP,NUM_SWEEPS,1,0,0)
290  ! THIS ROUTINE GETS 1024 I/O POINTS FROM THE HP8908A.
300  ! THESE POINTS ARE EASILY SPAaced IN TIME.
360  DIM Images(4,0,100)
370  !
380  ! DIS  ** Getting scaling information **
390  ! THE FOLLOWING INFORMATION IS USED TO CONVERT THE DATA
400  ! SENT BY THE ANALYZER INTO ACTUAL VOLTAGE VALUES.
410  OUTPUT HSTOP** "NO. 1 SCALE VECTOR;"
420  OUTPUT HSTOP** "WAV: DEF."
430  ENTER HSTOP,100,100,100,100,100,100,100,100,100,100,100,100,100,100,100
440  OUTPUT HSTOP** "WAV: IN."
450  ENTER HSTOP,100,100,100,100,100,100,100,100,100,100,100,100,100,100,100
460  OUTPUT HSTOP** "WAV: OR."
470  ENTER HSTOP,100,100,100,100,100,100,100,100,100,100,100,100,100,100,100
480  OUTPUT HSTOP** "VAR: DEF."
490  ENTER HSTOP,100,100,100,100,100,100,100,100,100,100,100,100,100,100,100
500  OUTPUT HSTOP** "VAR: IN."
510  ENTER HSTOP,100,100,100,100,100,100,100,100,100,100,100,100,100,100,100
520  OUTPUT HSTOP** "VAR: OR."
530  ENTER HSTOP,100,100,100,100,100,100,100,100,100,100,100,100,100,100,100
540  DIS  ** Gathering data...returning prembale**
550  FOR Sweep cnt1=1 TO NUM_SWEEPS
560  OUTPUT HSTOP** "WAV: "(cnt1+1:1024) "DATA:";
570  ENTER HSTOP USING "A:A;D:Dim:Wytes;
580  Irgetr-1:Q:Wytes1:K:Dimensions;
590  ENTER HSTOP USING images:
600  NEXT Sweep cnt1
610  DIS  ** Ending data...**
620  ENTER HSTOP USING "Buift"
630  ENTER HSTOP USING "Buift-1:1000"
640  ENTER HSTOP USING "Buift-1:1000"
650  ENTER HSTOP USING "Buift-1:1000"
660  ENTER HSTOP USING "Buift-1:1000"
670  NEXT Sweep cnt2
680  MAT Buift=Buift/buift;NUM:SWEEPS
690  !
700  ! DIS  ** Massaging data...**
710  CTR=1
720  !
730  REPEAT: ! SORT THE 1/0 PAIRS INTO SEPARATE ARRAYS
740  Qctr=1:Buift[ctr-2]
750  Qctr=1:Buift[ctr-2]
760  CTR=CTR+1
770  CTR=CTR-2
780  UNTIL CTR=NUM(SWEEPS/2)
790  !
```

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