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An Understandable Test Set for Making Basic Measurements on Telephone Lines

This new portable test set uses a digital processor to present direct-reading, autoranged measurements of level and frequency, substantially reducing operator errors. Other conveniences simplify set-up and operation.

by Michael B. Aken and David K. Deaver

CONTINUING EXPANSION OF THE world's telephone network intensifies the need for means of testing telephone lines *expediently*. Now more than ever, with the growth of data communications, operating companies and end users need test equipment that can check telephone lines quickly without requiring a lot of personnel training.

The HP Models 3551A (Fig. 1) and 3552A (Fig. 2) are dedicated test sets designed to fill this need. These instruments make basic measurements on voice-grade lines according to North American (Model 3551A) and CCITT (Model 3552A) standards. They measure tone level, noise level, and frequency, from which they obtain measurements of loss, attenuation distortion, message-circuit noise, noise with tone, noise to ground, and single frequency interference.

Both test sets include an oscillator, a frequency meter, a level meter, and the various filters required for voice-channel measurements. They can send a test signal while simultaneously measuring it in a loop-back set-up, or two can be used as a pair for one-way measurements. Combining the send and receive functions in one box makes the test set easier to carry and it also speeds measurements by making it possible to switch between send and receive without reconnecting anything and while maintaining the telephone line in an "off-hook" condition.

Design goals achieved with the realization of these test sets were:

Reduction of operator set-up time because of an easily-understood front panel;

Reduction of operator errors because of the autoranged, direct reading digital display;

Increase in accuracy because of the low-distortion test signal with settability within 1 Hz;

Increase in convenience because of the compactness, light weight (13 lbs), and choice of battery or line power.

Front Panel Clarity

A careful look at the front panel (Fig. 1) discloses how the telephone craftsman can tell the status of the instrument at a glance, and modify that status quickly with a minimum likelihood of making a wrong move.

The right portion of the panel has the controls for the send unit. Frequency is selectable within a 40-Hz-
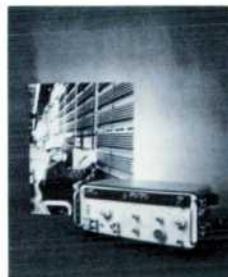
Cover: *Telephone channels need to be tested quickly, especially when restoring service on thousands of lines following a major disruption. Our thanks to the New York Telephone Company for the background photo of craftsmen cleaning 16,000,000 relay contacts contaminated by the recent fire. The instrument is Model 3551A Telephone Test Set, a number of which were used in restoring service. Also described in this issue is Model 5453A, a programmable, computerized telephone test system that uses digital signal analysis.*

Fig. 1. *Model 3551A Transmission Test Set makes basic measurements on telephone lines according to North American standards. The front panel is arranged to clarify operation of the instrument. The digital display is autoranged and automatically compensated for the selected impedance.*

to-60-kHz range and the amplitude is adjustable from −60 to +10 dBm. None of the controls is calibrated because the built-in measuring circuits enable readout of frequency and level with better resolution and accuracy than dial markings could provide. The frequency range switch also includes a position for quick selection of the fixed holding tone used in noise-with-tone measurements.

The central portion of the front panel is concerned with the type of measurement to be made on the received signal. One switch selects the measurement to be made (tone, noise with tone, message circuit noise, noise to ground) while the other switch selects one of four weighting networks. Measurements can be made on tones that have amplitudes ranging from −70 dBm to +15 dBm or on noise that ranges from 0 to +125 dBrn.

The left portion is concerned with the physical connection to the telephone lines. Two sets of terminals are provided to permit simultaneous send/receive measurements, each set consisting of a standard phone jack in parallel with a pair of 5-way binding posts. Either set may be used for measurements on a single pair. The FUNCTION switch selects the role of each set of terminals (send or receive) and it enables the roles to be interchanged without requiring any disconnecting and reconnecting of the lines. It also determines whether the receive line is to be bridged or terminated. A concentric switch selects the load impedance for a terminated line (and also establishes the send source impedance).

A set of clip posts for connecting a lineman's handset can be switched in parallel with the left set of terminals for dialing up a connection. A holding circuit is provided so a connection to a "wet" line can be

held in an off-hook condition while the line is used for either send or receive measurements.

The readout is an LED display that gives four-digit resolution in frequency, three-digit resolution in tone level, and two-digit resolution in noise level measurements. The quantity displayed (receive level or frequency, or send level or frequency) is selected by pushbuttons. Both frequency and level measurements are autoranging and automatically compensated for the impedance selected to give fast, direct readout of the measured quantity. No mental calculations are required on the part of the operator.

A monitor loudspeaker helps the craftsman identify single-frequency interference and, by the character of the sound, the source of other types of interference.

Battery and AC Power

Each of the instruments has internal rechargable

Fig. 2. *Model 3552A Transmission Test Set is fundamentally identical to the Model 3551A but has connectors, filters, and impedance levels that conform to CCITT standards.*
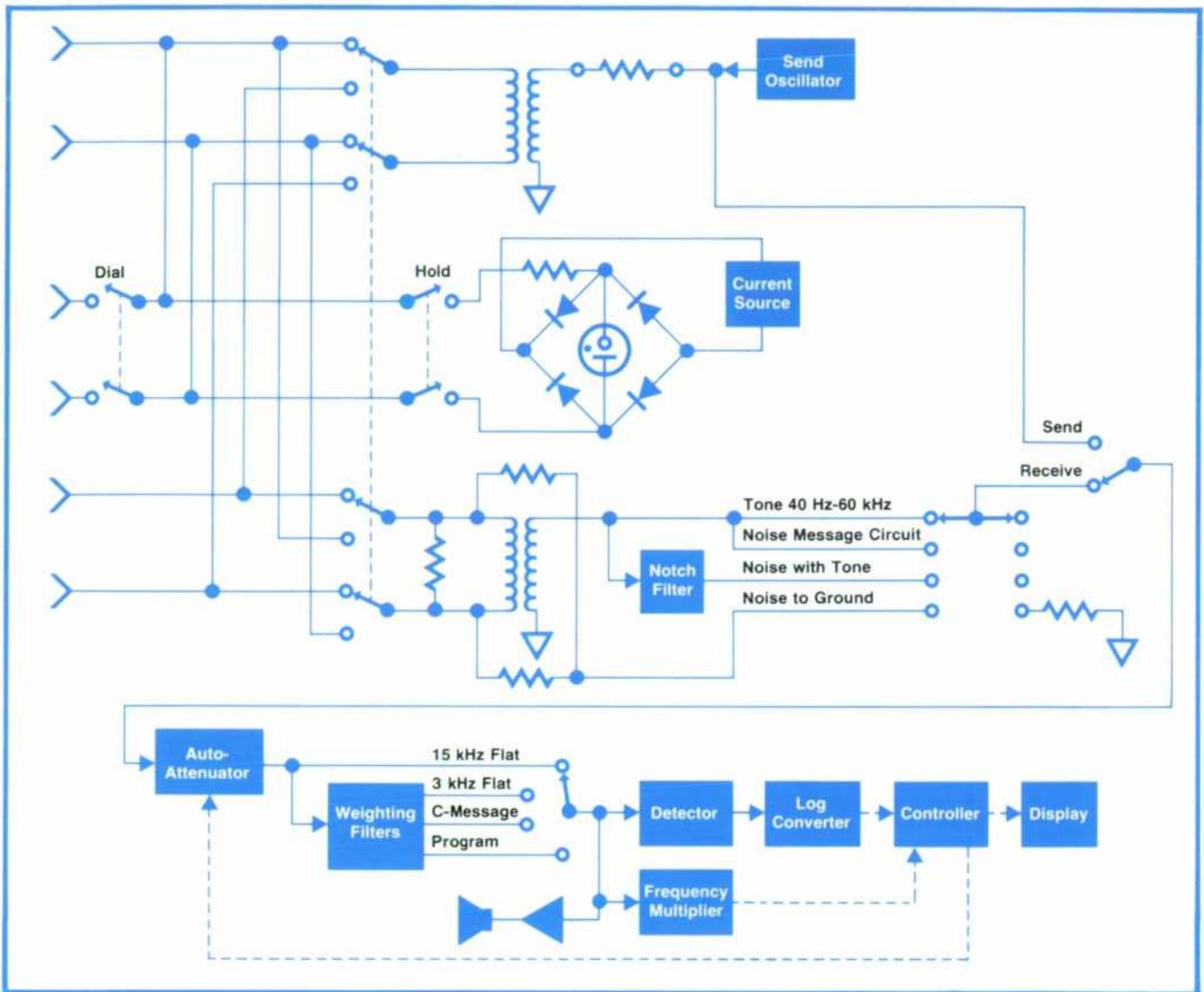
Fig. 3. *Simplified block diagram of the 3551A/3552A Transmission Test Sets. Signal processing is analog up to the detector, then processing becomes digital. The hold circuit is a current source that appears as a broadband high impedance to the telephone line while supplying the current necessary to hold central office relays. The diode bridge, protected against high line transients by the gas-discharge tube, functions as an automatic polarity switch for the hold circuit.*

batteries that can power the instrument for four to six hours on one charge. The instruments can also operate on ac lines of 100, 120, 220, or 240 volts.

In the new test sets, a level-sensing circuit monitors the battery voltage and shuts off the instrument whenever the voltage falls below a useful level. This prevents erroneous readings and it also prevents cell reversal from deep discharge.

This arrangement is considered preferable to meter monitoring because the NiCad batteries used maintain a fairly constant voltage during use and then lose voltage rather rapidly as they approach total discharge. With the usual meter monitoring, the operator would have to check the battery voltage quite frequently to avoid overlooking the onset of the

rapid voltage fall.

Internal Details

The two instruments are fundamentally the same except for certain characteristics that conform to the telephone measurement standards where the instruments are to be used. The Model 3551A has impedances, weighting filters, and a hold tone that conform to standards established by the telephone industry in North America. In most of the rest of the world, standards are set by the International Telegraph and Telephone Consultative Committee (CCITT) and the Model 3552A conforms to these standards.

The block diagram shown in Fig. 3 applies to both instruments. The received signal is filtered and detected in conventional analog fashion. The output of

the detector, however, is converted to a proportionate time interval in the logarithmic converter. The digital circuits measure this time interval to get a digital indication of the input signal level. From here on, the measurement information is manipulated digitally, with appropriate factors added so the number displayed gives the measurement in the desired units.

In a frequency measurement, the signal frequency is multiplied in a phase-lock loop so the counting circuits can accumulate enough counts in 50 milliseconds for 4-digit resolution. This enables a 10-per-second sampling rate, even at low frequencies.

One of the significant differences between these instruments and other telephone test sets is the use of a function generator as the send unit, rather than the traditional RC oscillator. The use of a function generator achieves significant cost and space savings. The basic function generator circuit was modified, however, to obtain a sine wave with very low distortion.

Triangles First

A schematic representation of the send unit's function generator is shown in the box on page 6. As in other function generators, a triangular waveform is generated by using constant currents to alternately charge and discharge a capacitor, shown as range capacitor C_R in the diagram. The triangular wave is shaped into a sine wave by a nonlinear network. Diodes in this network are biased at progressively higher levels so more and more attenuation is switched in as the triangular waveform moves towards its positive or negative limit. By suitable choice of the attenuation switched in by each diode, the triangle is rounded off to a sine wave.

Maintaining high sine-wave purity under field conditions required some modifications to the basic waveform-generating mechanism. To begin with, the sine shaper is compensated for temperature changes by diodes that adjust the voltage on the biasing networks to compensate for the change in diode forward voltage drop caused by temperature changes.

For optimum operation of the sine shaper, the up slope of the triangle wave must be exactly equal to the down slope and the waveform must be centered on the zero level (equal positive and negative excursions). Circuits for maintaining these conditions are designed into the function generator. These are described in the box on page 6.

As a result of these measures, total harmonic distortion in the send unit output is more than 50 dB below the fundamental within the telephone voice band and at least 40 dB below outside that band. These specifications are held over an operating temperature range of 0°C to 55°C.

Level Detection

As noted in the block diagram of Fig. 3, the received signal is appropriately filtered and adjusted
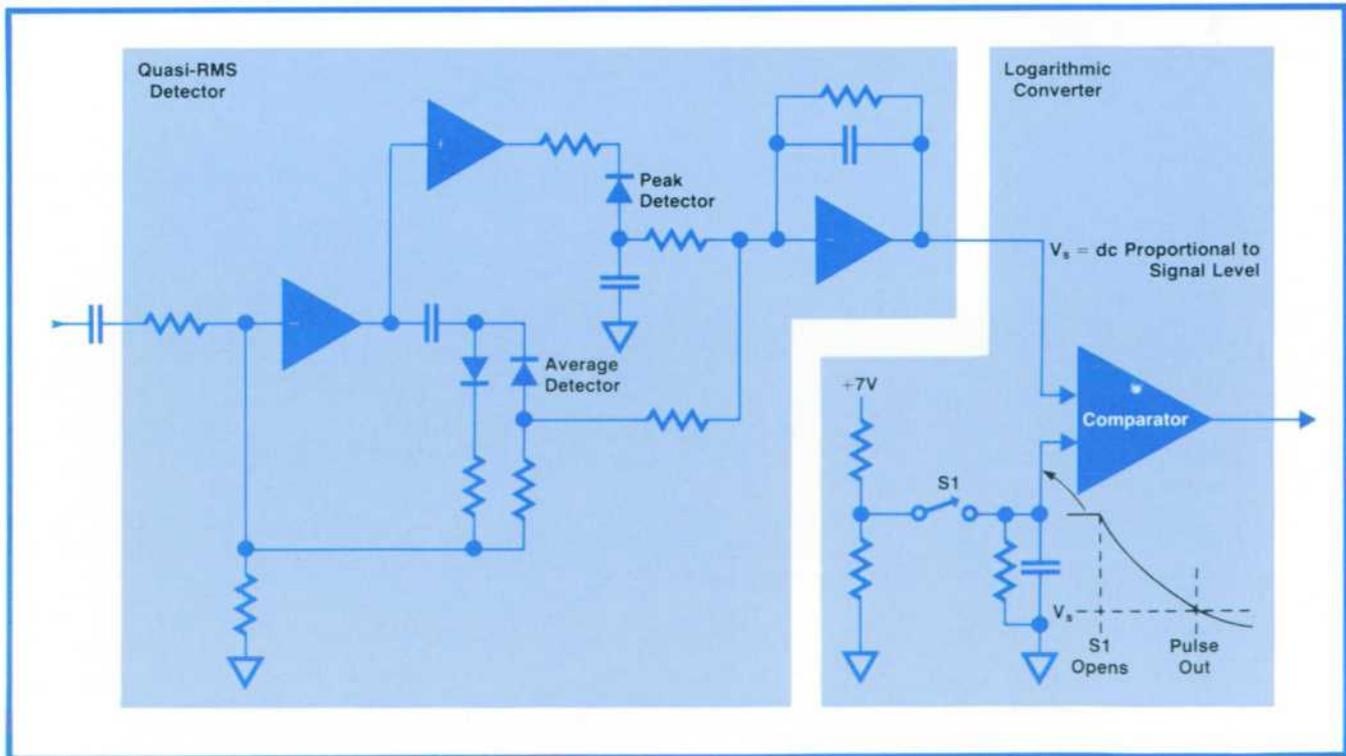

Fig. 4. *Detector combines the outputs of peak and average detectors to derive a quasi-rms indication. The detector output is converted to a proportionate time interval by the logarithmic converter.*

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A Function Generator with a Well-Defined Output

Definite space-saving and cost advantages result from using a function generator as the send unit's oscillator in the Model 3551A/3552A Transmission Test Set. Certain modifications, however, had to be made to the basic circuit to assure the waveform purity required for telephone tests.

A simplified diagram of the function generator is shown below. Positive and negative currents are switched by transistors Q1 and Q2 to alternately charge and discharge capacitor C_R, thereby generating a triangular waveform. To minimize switching transients, steady current flow is maintained by operating transistors Q1 and Q2 in a bridge configuration with Q3 and Q4. This arrangement sinks one current to ground while the other is charging the capacitor and vice-versa.

The transistors are turned on and off by a bistable switch that changes states when a comparator indicates that the triangle waveform has reached the same level as that being held by the switch. The amplitude of the triangular waveform is thus determined by the bistable switch, a precision circuit that maintains a well-defined level in either of its two states.

The frequency is determined by the rate at which the capacitor charges and discharges. The vernier frequency control changes the charge and discharge currents. Ranges are changed by switching in capacitors of different values.

The triangular waveform is shaped into a sine wave by the nonlinear network described in the text preceding. To assure proper operation of the sine shaper, the triangular waveform must be symmetrical. Equal positive and negative waveform excursions (x-axis symmetry) are assured by integrating the triangular waveform and using the resulting dc level to modify the lower steady-state level in the bistable switch. The waveform's peak negative excursion is thus adjusted to equal the magnitude of the peak positive excursion.

Maintaining equal up and down slopes (y-axis symmetry) is accomplished by sensing the symmetry of the square wave. Referring to the y-axis symmetry circuit in the diagram, current I_s flows into the adjacent integrator when the square wave is at the upper level, reverse-biasing diode D1. When the square wave is at the lower level, the reverse bias is removed from diode D1, allowing the lower current source to draw a current equal to $2I_s$ through diode D1, with half of the current (I_s) being drawn from the integrator. Thus, as long as the waveform is symmetrical, the average integrator output is zero. If the waveform were not symmetrical, a net charge would remain on the integrator output, which would add to or subtract from the charging current in the triangle generator. The up slope of the triangle is thereby altered to make it match the down slope.
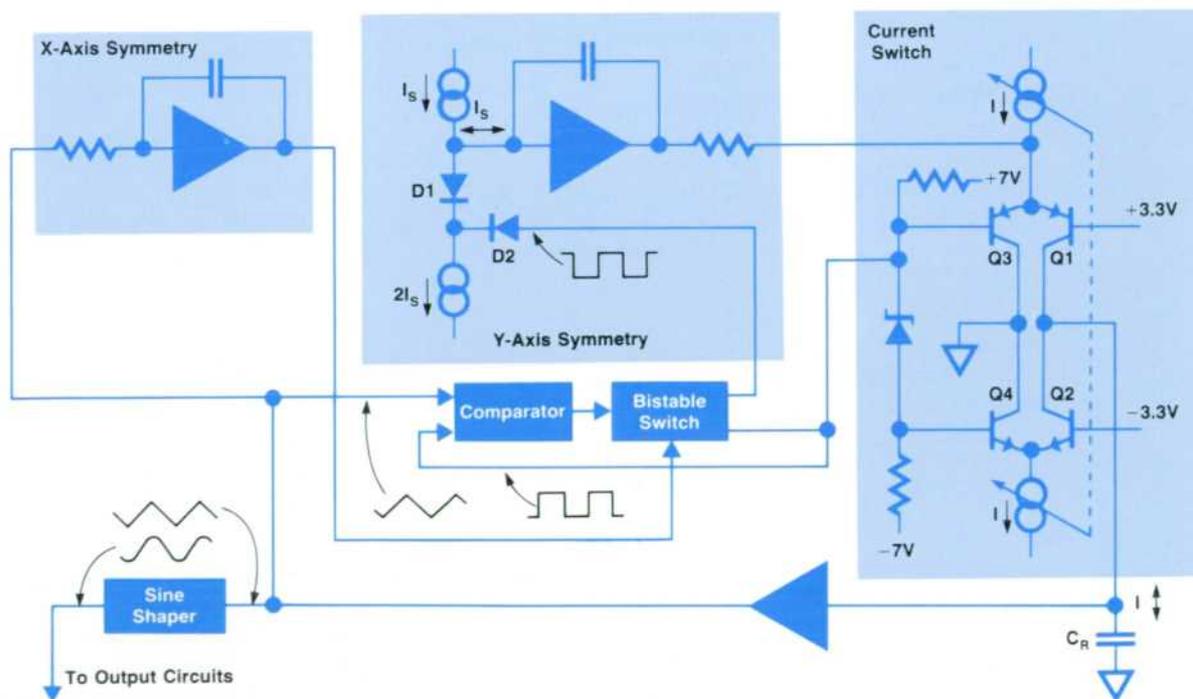
in gain before being applied to the detector. For noise measurements, the detector functions as a quasi-rms type that derives the equivalent of an rms measurement by combining the outputs of peak and average detectors in accordance with Bell System Technical Reference PUB 41009.

The peak detector (Fig. 4) is a diode that charges a capacitor to the negative peak of the waveform. The average detector integrates negative half-cycles of one waveform to get an average value. The summing resistors at the input to the integrator determine the ratio of peak to average in the combined result. During tone measurements, only the average detector is used.
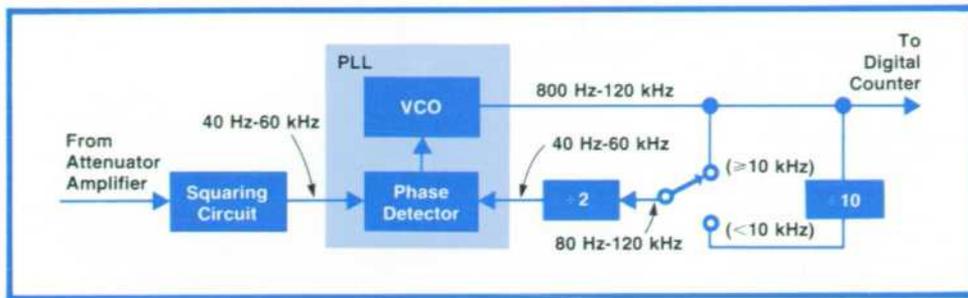
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Fig. 5. *Frequency multiplier generates an output two times the input for inputs of 10 kHz and higher, and 20 times higher for inputs below 10 kHz.*

The detected dc level is then applied to the log converter. This compares the detectors' dc level to the voltage on a discharging capacitor, generating a pulse when the two are equal. Ten times per second during tone level measurements, switch S1 (Fig. 4) closes long enough to charge capacitor C_1 to a fixed level. When S1 opens, C_1 discharges and when it falls to the level of the detector voltage, a pulse is generated. The time interval between the opening of S1 and the comparator pulse is thus inversely proportional to the absolute value of the input voltage and, since the C_1 discharge curve is exponential, to the logarithm of the input voltage. The digital circuits measure this time interval to derive the number for display. The 100-kHz clock frequency gives a measurement resolution of 0.02 dB, which is truncated to give a display resolution of 0.1 dB.

During noise measurements, an additional low-pass filter is switched in at the input to the log converter to provide more averaging for the noise signal. Switch S1 is then activated only two times per second.

The digital circuits also use the output of the log converter to sense when the attenuator range should be changed. If the time between the opening of switch S1 and the comparator pulse is less than 5 ms (signal too large), the attenuator is up-ranged. If the time is greater than 20 ms (signal too low), the attenuator is down-ranged. The 15-ms interval between these points is equivalent to 15 dB, giving a comfortable overlap of the 10-dB range on each attenuator step.

The attenuator consists of resistive dividers with taps switched by an eight-channel analog multiplexer under control of the digital system. The control sequence is such that an amplitude measurement and range correction is always made before a frequency measurement is made. The frequency measuring circuits are thus assured of a suitable signal level.

Fast-Responding Frequency Measurements

To get 1-Hz resolution in a conventional frequency-counter measurement of an audio frequency, say 4 kHz, a one-second counting time is required. A sampling rate of 10 per second was desired for the Models 3551A/3552A so the results of adjustments to

the telephone line are immediately apparent to the craftsman. The counting time was thus made 50 milliseconds, which allows time for an amplitude measurement within each 100-millisecond measurement interval. To achieve 1-Hz resolution in this time interval, input frequencies lower than 10 kHz are multiplied by a factor of 20 before counting. Input frequencies of 10 kHz and higher are multiplied by 2, giving 10-Hz resolution with the four-digit counting circuits.

The frequency-multiplication circuit is shown in Fig. 5. A commercially-available integrated-circuit phase-lock loop is at the core of the circuit. It has a voltage-controlled oscillator controlled by a phase detector that compares the input signal to a divided-down version of the VCO output frequency. The VCO is thus locked to a multiple of the input frequency.

Digital Control

The operating simplicity of these instruments results from the use of a digital processor to manipulate the raw measurement information. The processor monitors the signal level and frequency and the front-panel control settings, and uses this information to derive control signals for the measurement routines and for the display.

The digital processor (Fig. 6) is an algorithmic state machine (ASM) that uses MSICs (medium-scale integrated circuits) and 8000 bits of memory in low-cost ROMs. It is divided into two parts, a control section and a display section, although functions overlap somewhat.

A four-digit counter that is part of the display section performs measurements of both level and frequency. It counts 100-kHz pulses for the duration of the log converter's measurement interval to derive a digital number proportional to signal level. During the 50-ms frequency measuring interval, it counts the output of the frequency-multiplier circuit (Fig. 5).

At the end of a frequency measurement interval, the counter's contents are latched into a register and held there for direct application to the display. The contents of the latch register are scanned digit-by-digit and applied to a seven-segment decoder that drives the display LEDs one at a time. Scans occur 2500 times per second.

Fig. 6. *Simplified block diagram of Test Set's digital circuits.*

At the end of an amplitude measurement, the register contents are used as an address to find a new number in the display ROM according to the measurement being made. For example, in tone measurements, a 0-dBm input signal results in a log converter time interval of 10 ms (1000 counts). This is displayed as 0 dBm. A higher count (longer time interval, lower amplitude) is interpreted by the display ROM as a larger number (dB below 0 dBm) and it adds a minus sign to the display. A lower count (shorter time interval, higher amplitude) is also displayed as a larger number (dB above 0 dBm) but with a plus sign. Although the counter is unidirectional, it appears to behave as a reversible counter because of the ROM processing.

Noise measurements are processed in a similar manner so the correct number is displayed. In the case of measurements of noise-to-ground, the ROM adds 40 dB to the measurement number to correct the reading for the signal attenuation caused by the noise-to-ground input configuration (see Fig. 3). The craftsman is never required to add this correction mentally.

Using firmware to process the numbers, rather than adders, registers, and other hardware, reduced the parts count significantly and hence reduced the cost.

The control section of the digital processor uses a 4K ROM that contains all of the instructions for the level, noise, and frequency measurements. Through the qualifier select block, it monitors timing signals and determines the proper frequency range and the points at which autoranging is initiated. It partitions the 100-ms sampling interval into the 25-ms signal amplitude measurement interval and the 50-ms frequency measurement interval. It issues steady-state command voltages for opening and closing switches, and pulsed commands for initiating time-related functions.

Test and Calibration

The control section ROM also contains instructions for a progressive series of tests for troubleshooting both the digital components and analog subsystems. These are internally-accessible tests, which means that they cannot be accessed by the operator from the front panel but they can be used as a troubleshooting tool by maintenance personnel, either in the shop or in the field. Tests may be conducted in either a fixed informational display mode, which indicates proper operation of the test routines and thus the instrument, or a dynamic response mode using an oscilloscope, which allows individual IC's, circuits, and subsystems to be examined at normal operating repetition rates. Some of the tests that can be performed are:

■ High-speed exercising of all transfers, resets, command outputs, and flip-flops to assure their proper operation.

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- Monitoring the display ROM outputs to check proper operation of the ROM and its associated circuitry.
- Fast or slow repetitive operation of the analog autoranging circuitry to check proper gains and transient responses.

One of the cost-saving features of these instruments is the inclusion of two test sockets that allow connection to a calculator-controlled test system. The inclusion of a digital controller in the Models 3551A/3552A made it relatively simple to make most of the pertinent information available to the HP Interface Bus.[1] It was thus possible to design a calculator-controlled test system that assures that the necessary calibrations are performed. It also checks more points than would have been possible manually while at the same time reducing test time. The system automatically sets a digital voltmeter and a synthesizer to the proper ranges, checks the front-panel control settings of the instrument under test, tells the technician the adjustment to make, and checks that the calibration is within prescribed limits.

Acknowledgments

The authors would like to acknowledge the contributions of Ray Hanson for the design of the send oscillator and as the group leader of the 3551A. Dick Huffman provided the mechanical design.

Reference

1. D.W. Ricci and P.S. Stone, "Putting Together Instrumentation Systems at Minimum Cost," Hewlett-Packard Journal, January 1975.

David K. Deaver
Dave Deaver joined HP in 1969 after earning his BSEE degree at Washington State University. Since being with HP, he contributed to the designs of the Models 3575A Gain/Phase Meter and the 3570A Network Analyzer before joining the 3551A project. He is working towards his MSEE degree at Colorado State University in the HP Honors Co-op program. Dave plays basketball in the Loveland, Colorado, community intramural program and carries this activity over into community youth work, refereeing Saturday morning basketball games. He and his wife have one daughter, 2.

Michael Aken
With HP since 1966, Mike Aken worked on voltmeters (3450A and 3480A) and the 3570A Network Analyzer before joining the 3551A project. A graduate of the University of Wisconsin (BSEE), he earned his MSEE at Colorado State University in the HP Honors Co-op program. Married, and with three children, 10, 8 and 5, Mike enjoys gardening, both outdoor and indoor with fluorescent lights, and he plays some tennis.

SPECIFICATIONS
Model 3551A/3552A Transmission Test Set

Receive Section

LEVEL MEASUREMENTS
FREQUENCY RANGE: 40 Hz to 60 kHz
DYNAMIC RANGE: +15 dBm to −70 dBm
RESOLUTION: 0.1 dB
SAMPLE RATE: 10/second
DETECTOR TYPE: average responding
ACCURACY:

INPUT LEVEL (dBm)	FREQUENCY			
	40 Hz 100 Hz	1 kHz 10 kHz 20 kHz	60 kHz	
+15		±0.1 dB	±0.3 dB	
−30	±0.5 dB			
−10		±0.3 dB	±0.5 dB	

200 Hz
135Ω IMPEDANCE NOT SPECIFIED BELOW 200 Hz

NOISE MEASUREMENTS (3551A)
DYNAMIC RANGE
  Message circuit noise: 0 dBm to +85 dBm
  Noise-with-tone: 10 dBm to +85 dBm (600Ω, 900Ω)
  Noise-to-ground: +40 dBm to +125 dBm
RESOLUTION: 1 dB
SAMPLE RATE: 2/second
DETECTOR TYPE: Quasi RMS
ACCURACY
  Message circuit noise: ±1 dB (+20 dBm to +85 dBm), ±2 dB (0 dBm to +20 dBm).
  Noise-with-tone: ±1 dB (+20 dBm to +85 dBm), ±2 dB (10 dBm to +85 dBm).
  Noise-to-ground: ±1 dB (+60 dBm to +125 dBm), ±2 dB (+40 dBm to +60 dBm).
WEIGHTING FILTERS: C-message, 3 kHz flat, 15 kHz flat, program.

NOISE MEASUREMENTS (3552A)
DYNAMIC RANGE
  Message circuit noise: −90 dBm to −5 dBm

Noise-with-tone: −80 dBm to −5 dBm (600Ω, 900Ω).
Noise-to-ground: −50 dBm to +35 dBm.
Resolution: 1 dB
Sample rate: 2/second.
Detector type: RMS responding
ACCURACY
  Message circuit noise: ±1 dB (−70 dBm to −5 dBm), ±2 dB (−90 dBm to −70 dBm).
  Noise-with-tone: ±1 dB (−70 dBm to −5 dBm), ±2 dB (−80 dBm to −70 dBm).
  Noise-to-ground: ±1 dB (−30 dBm to +35 dBm), ±2 dB (−50 dBm to −30 dBm).
WEIGHTING FILTERS: Telephone (CCITT Psophometric), 3 kHz flat, 15 kHz flat, programme (CCITT).

FREQUENCY MEASUREMENTS
FREQUENCY RANGE: 40 Hz to 60 kHz
DYNAMIC RANGE: +15 dBm to −70 dBm
RESOLUTION: 1 Hz (40 Hz to 10 kHz), 10 Hz (10 kHz to 60 kHz).
SAMPLE RATE: 10/second
ACCURACY: ±1 count

Send Section

FREQUENCY RANGE: 40 Hz to 60 kHz
RANGES: 40 Hz to 600 Hz, 200 Hz to 6 kHz, 2 kHz to 60 kHz, 1004 Hz fixed (3551A) or 800 Hz (3552A). Other frequencies available for 3552A.
RESOLUTION: 1 Hz (40 Hz to 10 kHz), 10 Hz (10 kHz to 60 kHz).
HARMONIC DISTORTION: >−50 dB THD (100 Hz to 4 kHz), >−40 dB THD (40 Hz to 100 Hz and 4 kHz to 20 kHz), >−55 dB (all harmonics 100 Hz to 4 kHz), >−60 dB THD (1004 Hz fixed).
ACCURACY: ±1 count
LEVEL RANGE: −10 dBm to −60 dBm (40 Hz to 60 kHz), +6 dBm to −60 dBm (1004 Hz fixed)
RESOLUTION: 0.1 dB

ACCURACY:

OUTPUT LEVEL (dBm)	FREQUENCY		
	40 Hz 100 Hz	1 kHz 4 kHz 10 kHz 20 kHz	60 kHz
−30	±0.5 dB	±0.2 dB	±0.5 dB
−60	±1 dB	±0.3 dB	±1 dB

200 Hz
135Ω IMPEDANCE NOT SPECIFIED BELOW 200 Hz

General

MONITOR: built-in speaker monitors received or transmitted signal
BALANCED IMPEDANCES: 135Ω (3551A), 150Ω (3552A), 600Ω, 900Ω
BRIDGING LOSS: >0.2 dB
RETURN LOSS: >−30 dB
LONGITUDINAL BALANCE: >60 dB at 6 kHz
HOLD CIRCUIT: 24 milliamps constant current; >50 kΩ impedance, resistive fuse protection.
INPUT/OUTPUT PROTECTION: blocks 300 V dc, maximum longitudinal voltage: 200 V rms.
BATTERY SUPPLY: 4-6 hours continuous operation on internal rechargeable batteries at 25°C. Battery drain is automatically turned off when discharged below proper operating level. Complete recharge in 12 hours.
AC LINE: 100, 120, 200, 240 V ±10%, 48 Hz to 440 Hz; 14 VA
TEMPERATURE RANGE:
  OPERATING: 0°C to 55°C (32°F to 130°F).
  STORAGE: 20°C to 65°C (−4°F to 149°F).
RELATIVE HUMIDITY: 0 to 95% (<100°F, >40°C).
WEIGHT: Net: 6.6 kg (13 lb)
DIMENSIONS: 133 mm H × 343 mm W × 254 mm D with front-panel cover (5.25 × 13.5 × 10 inches)
PRICES IN U.S.A.: 3551A, $1750; 3552A, $2000
MANUFACTURING DIVISION: LOVELAND INSTRUMENT DIVISION
  P.O. Box 301
  815 Fourteenth Street, S.W.
  Loveland, Colorado 80537

A Computer System for Analog Measurements on Voiceband Data Channels

Besides making nine data-channel performance tests automatically in less than two minutes, this new Transmission Parameter Analyzer is capable of a much broader range of measurements.

by Stephan G. Cline, Robert H. Perdriau, and Roger F. Rauskolb

MANKIND TODAY POSSESSES a truly staggering ability to disseminate information. Much of this ability depends upon networks that transmit information in the form of electrical signals to the far corners of the earth and deep into space. Over the past decade, it has become necessary to transmit a growing volume of information at higher speeds and with greatly increased accuracy and reliability. This has led to the imposition of increasingly stringent performance requirements on the transmission networks and the components that comprise them.

The 5453A Transmission Parameter Analyzer (TPA), Fig. 1, has been developed to aid in the design, manufacture, installation, and maintenance of today's high-performance voice-grade communication channels and components. Transmission parameters are the properties of an electrical path that must be suitably controlled if information is to be successfully transmitted over the path. The path may be a simple amplifier, for which frequency response, noise, and distortion are the primary parameters of interest, or it may be as complex as a long-haul telephone channel that must be optimized for high-speed data transmission.

The 5453A TPA performs digital signal analysis, measuring signal properties using computational techniques rather than analog circuitry. No hardware detectors, demodulators, or signal generators of the type normally found in analog instrumentation are incorporated in the 5453A. New measurements may be implemented, or existing measurements modified, purely through software. Programs can be written in either FORTRAN or BASIC together with a simple calculator-like language. The 5453A also offers significant advantages in terms of speed and accuracy when compared to equivalent analog instrumentation.

The system is capable of both stimulus-response (network analyzer) or response-only (spectrum analyzer, power meter, counter) measurements. A representative list of measurements appears in Table I. There are two categories, one consisting of general measurements that may be useful in a broad range of applications, and the other consisting of nine characteristics of voiceband data channels that are commonly measured in North America. The 5468A Trans-
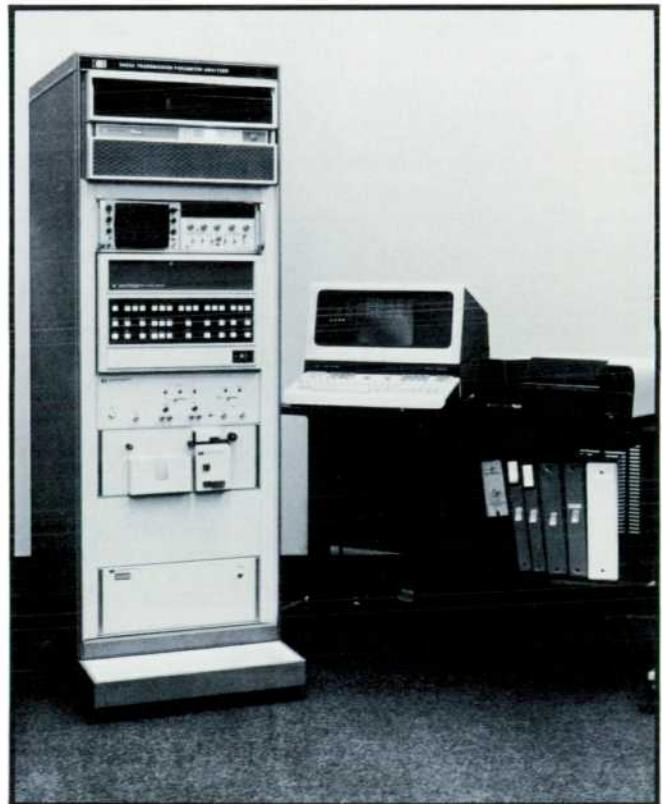
Fig. 1 *Model 5453A Transmission Parameter Analyzer is both a general-purpose stimulus-response test instrument and a special-purpose analyzer for performance tests on voiceband data channels and components. Table I lists some of its capabilities.*

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ponder (see box, page 16) is used with the TPA for many of the data-circuit measurements.

A simple block diagram of the system appears in Fig. 2. A digital-to-analog converter (DAC), together with suitable filtering and impedance matching, generates the desired stimulus. On the response side of the device being tested, an analog-to-digital converter (ADC) samples the incoming waveform and prepares it for digital processing. The mass memory provides storage for measurement and analysis programs, test stimuli, test results, and other data that may be required for a measurement, such as digital filters. A CRT terminal serves as the sole operator interface. From it, programs can be prepared and executed and tabular results displayed. No manual controls are present or necessary. An optional CRT display provides graphical output.

Stimulus Generation

Virtually any desired stimulus may be quickly and easily designed from the CRT terminal. The stimulus may be as simple as a sine wave or as complex as pseudorandom noise. It may be described as a waveform in the time domain or as a spectrum in the frequency domain. In the latter case, the user has complete control of both the amplitude and the phase of each spectral component.

Spectra and the corresponding waveforms can be designed in minutes, stored in the mass memory, and retrieved either on command from the operator or automatically by the measurement program. Before output, the waveform is represented in the computer memory by a block of 16-bit words, each word representing one time sample of the waveform. To convert this to an analog signal, the 5453A has a 13-bit DAC followed by programmable gain circuitry. A combination of block scaling and gain setting is used to achieve the desired peak or rms power output. Signals can be generated over a range of 0 to −40 dBm with distortion products down 60 dB.

The number of words per block is variable in powers of 2 from a minimum of 64 to a maximum of 4096. The number is selected along with the scanning rate to achieve the frequency range and resolution required in a given application. Generation of the test signal is accomplished by causing the program to read the block out through one of the computer's high-speed direct memory access (DMA) channels to the DAC. This process may be continued for as long as desired, resulting in a periodic signal being applied to the test device. The frequency range is limited by the settling time of the DAC and the DMA rate of the computer. Frequencies up to 10 kHz may be generated by the 5453A.

Table I
Representative Measurement Capabilities of the 5453A

Gain/Loss	Nonlinear Distortion
Phase	Impedance
Envelope Delay	Frequency Modulation
Frequency	Phase Modulation
Power	Amplitude Modulation
Noise	Conversion Loss

Characteristics of Four-Wire Data Circuits
Measured by the 5453A/5468A

Attenuation Distortion	Phase Jitter
Envelope Delay Distortion	Intermodulation Distortion
Level	Frequency Shift
Message Circuit Noise	Single-Frequency Interference
C-Notched Noise	
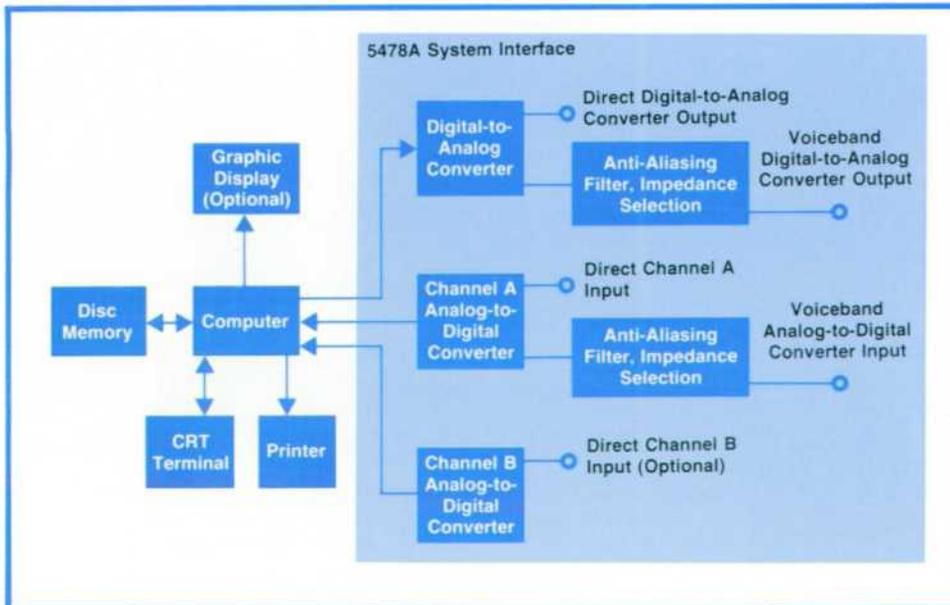
Fig. 2. *Transmission Parameter Analyzer block diagram. A digital-to-analog converter provides stimulus signals for the network being tested. Analog-to-digital converters sample the network's response. Parameters of interest are then computed digitally.*

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Digital Processing

On the response side of the 5453A, the incoming waveform from the test device is sampled by the ADC and converted to a block of 16-bit words representing successive time values of the input. The incoming waveform may have been generated by the DAC and distorted by the test device, or it may be an external signal. From this point, digital processing in either the time domain or the frequency domain is used to extract the pertinent information.

Because sampling is used as the means of gathering the raw data, we must, of course, be aware of the constraints imposed by aliasing, leakage, and quantizing noise.[1] The balanced, voice-frequency ports of the 5453A are provided with seven-pole elliptical filters that keep aliased products down at least 50 dB. For applications outside of the filter frequency range, the direct DAC output and ADC inputs must be provided with suitable anti-aliasing filters. Input frequencies greater than 100 kHz can be accommodated. Leakage is reduced by using Hanning or other appropriate windows on the data or, in some cases, by measuring the amount of leakage and accounting for it. Dynamic range greater than 70 dB is obtained and the system noise floor over the voice frequency band is approximately −90 dBm.

Digital signal analysis, by its very nature, involves operations on or between blocks of data words. These operations include block arithmetic, forward and inverse Fourier and Hilbert Transforms, power spectrum, convolution, correlation, integration, and so on.[1,2] In most practical situations, an ordered sequence of such operations must be performed on the raw input data. Programs to accomplish this may be written in FORTRAN. However, an alternative software approach, developed for the 5453A, provides a simple keyboard language that may be used to call for any desired sequence of block operations. The name "keyboard" derives from the fact that any block operation may be programmed by pressing at most two keys on the CRT terminal. Each block opera-

tion can be executed and the results displayed immediately upon entry. In this mode the 5453A is used very much like a general-purpose scientific calculator. Engineering personnel can learn to operate the system in one or two hours.

Once the desired keyboard program has been written, it can be executed directly or, more typically, it can be stored in the disc memory and retrieved and executed using a CALL statement from a FORTRAN or BASIC controlling program. Both the controlling and keyboard programs have access to any data blocks stored in the disc memory. The disc memory is also used to transfer data from one program to another. In this manner, measurement data resulting from the execution of a keyboard program is available to the controlling program for further computation, formatting and output, or decision making. In addition, data may be synthesized by the controlling program and passed to a keyboard program for use in a specific measurement. The disc memory is capable of storing a large number of keyboard programs, any one of which can be executed at will by the controlling program. The result is that powerful digital signal analysis capabilities are now available in the context of standard engineering-oriented computer languages.

The number of possibilities for digital processing of the raw data is large and they cannot all be discussed in this article. We will discuss two examples that illustrate processing of steady-state and random signals and then look at an example of using the 5453A to generate or simulate a desired impairment.

Measuring Insertion Loss and Phase

As a first example, suppose it is desired to measure the insertion loss and phase of a two-port network. Insertion loss and phase are defined as follows:

$$\text{Insertion Loss} = 20 \text{ Log } [V_o(f)/V_N(f)] \qquad (1)$$

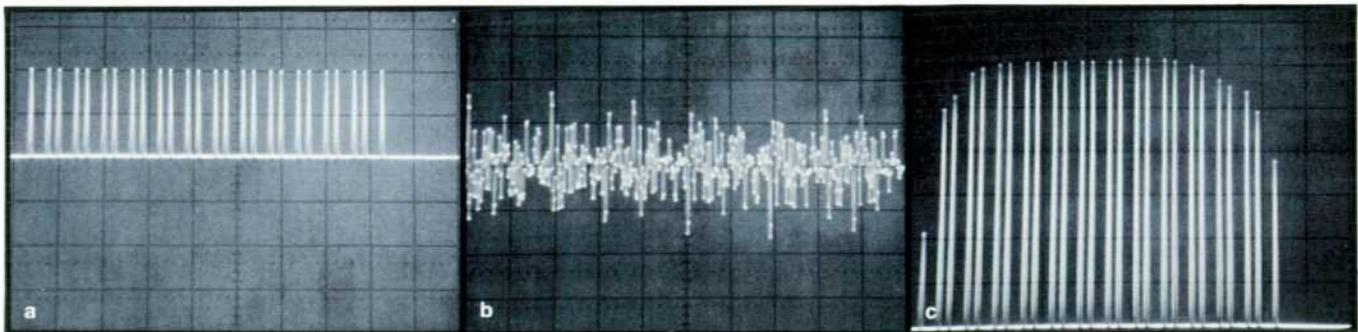$$\text{Insertion Phase} = [\phi_o(f) - \phi_N(f)] \qquad (2)$$

Fig. 3. *A typical insertion loss measurement on a two-port network showing the spectrum (a) of the test signal generated by the TPA, the test signal itself (b), and the network's insertion loss (c) computed by the TPA.*

where the "o" subscript refers to conditions at the load with the source directly connected, and the "N" subscript refers to conditions at the load with the network inserted. V(f) and ϕ(f) are voltage and phase expressed as a function of frequency. Further assume that the measurement is to be made at the frequencies contained in the spectrum of Fig. 3a.

A simple program to accomplish this measurement might first instruct the operator to bypass the network and connect the source directly to the load. It would then generate the waveform of Fig. 3b, corresponding to the spectrum of Fig. 3a. Next it would sample the DAC output, deriving a 512-word block of data (representing, in this case, a 64-ms time record), and compute the complex spectrum. In practice, several such records would be sampled and averaged to reduce the effect of external noise. The resulting averaged spectrum would be saved, the operator instructed to insert the network, and the process repeated. We now have two complex spectrums, $V_o(f)/\phi_o(f)$ and $V_N(f)/\phi_N(f)$. Performing the calculations indicated in equations 1 and 2 yields the desired result. Accuracies of ±0.1 dB and ±0.2 degree are obtainable, and the measurement can be accomplished in only a few seconds. Fig. 3c illustrates the results of an insertion-loss measurement on a simulated communication channel.

Noise Measurements

The measurement of noise is perhaps one of the most common maintenance activities in telecommunications, and the 5453A offers several capabilities in this area. A conventional measurement of noise might be modeled as shown in Fig. 4. In the case of a telecommunication channel, the input signal spectrum $S_{xx}(f)$ may be zero (input terminated), or it may represent a holding tone intended to bias compandored facilities to their normal operating points for continuous signals. In the latter case, the tone is removed by including a notch at the appropriate frequency in the transfer function of the weighting network. In either event, the weighted spectrum $S_{yy}(f)$ is indicated on an rms-responding power meter.
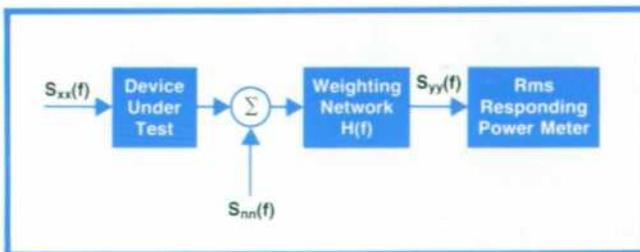
Fig. 4. *Model illustrating the measurement of noise. The $S_{ii}(f)$ represent complex voltage spectra as functions of frequency. The transfer function of the weighting network is H(f).*

From the model we write:

$$S_{yy}(f) = H(f) * [S_{xx}(f) + S_{nn}(f)] \qquad (3)$$

or, for $S_{xx}(f) = 0$

$$S_{yy}(f) = H(f) * S_{nn}(f) \qquad (4)$$

Since we are interested in power, we multiply each factor in equation 4 by its complex conjugate and write:

$$G_{yy}(f) = |H(f)|^2 * G_{nn}(f) \qquad (5)$$

In words, the weighted noise power spectrum is equal to the unweighted power spectrum multiplied by the squared magnitude of the transfer function of the weighting network.

The measurement is implemented with the 5453A TPA by first causing the TPA to gather a record (data block) representing the waveform associated with $S_{nn}(f)$. From this raw data, the complex spectrum $S_{nn}(f)$ is computed, followed by computation of the power spectrum $G_{nn}(f)$. In practice, this process is repeated several times and the computed $G_{nn}(f)$ are averaged to obtain a reliable estimate of the noise power spectrum. With an estimate of $G_{nn}(f)$ available, the desired weighting is applied in accordance with equation 5. The weighting function, $|H(f)|^2$, may be obtained by actual measurement of a physical network or it may be computed from the ratio of polynomials that describe the network. In either case, it is most often stored in the mass memory and used as needed. The resulting data block, representing $G_{yy}(f)$, is then integrated to obtain the total (mean square) weighted noise power. Specific frequencies, such as 60 Hz and its significant harmonics, may be eliminated by excluding them from the limits of integration. The resultant data block is then passed, via the mass memory, to the controlling program, where it is converted to the appropriate units (dBm, dBrnC, etc.) for output.

Each of the steps is called for by simple keystrokes and, once programmed, may be repeated as desired. It is possible to apply any number of weightings without repeating the measurement. The power spectrum is available and may be scanned by the controlling program to determine the frequency and level of any interfering tones that may be present. A typical flat-weighted noise power spectrum with an interfering tone at 1 kHz and -53 dBm is illustrated in Fig. 5. Finally, if $S_{xx}(f)$ is non-zero—representing, for example, the output of a data set—it is possible to check for proper operation as regards both the frequencies and power level transmitted.
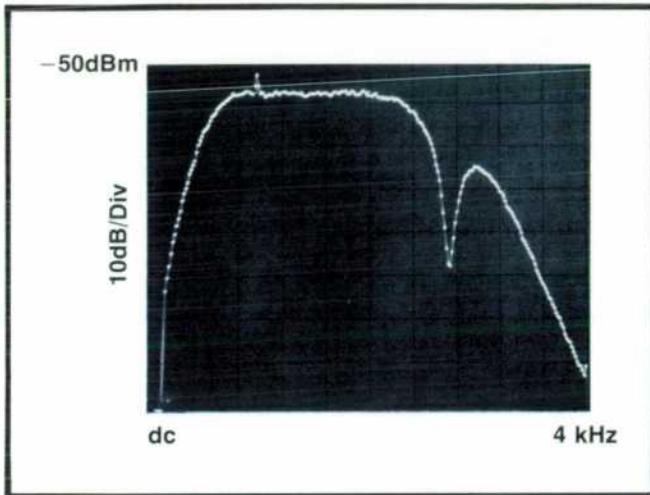
13

Fig. 5. *Typical flat-weighted noise power spectrum computed by the TPA. An interfering tone is apparent.*

Simulating Impairments

Digital signal analysis can also be used to simulate known impairments. Fig. 6a shows the power spectrum of a clean test signal containing energy at 703 and 1172 Hz. Such a signal might be used as a stimulus when performing measurements of intermodulation distortion.

Suppose that we have devised a system for measuring the second-order intermodulation distortion of a device using the signal in Fig. 6a as a stimulus, and we wish to test this measurement system. To do this we need a means of creating known and variable degrees of second-order distortion. The design and construction of a physical device to do this is expensive and time-consuming. An alternative is to use the computational ability of the 5453A to generate known distortions.

We begin by assuming a nonlinear device transfer function given by:

$$e_o(t) = a_1 e_i(t) + a_2 e_i^2(t) \qquad (6)$$

where a_1 is the linear component of the transfer function and a_2 is related to the degree of second-order nonlinearity. Next, we describe our test stimulus as:

$$e_i(t) = A\cos\alpha t + B\cos\beta t \qquad (7)$$

Substituting (7) into (6), applying the appropriate identities, and assuming $A=B$ for simplicity, we obtain:

$$e_o(t) = a_2 A^2 + a_1 A(\cos\alpha t + \cos\beta t)$$

$$+ \tfrac{1}{2} a_2 A^2 (\cos 2\alpha t + \cos 2\beta t)$$

$$+ a_2 A^2 [\cos(\alpha-\beta)t + \cos(\alpha+\beta)t] \qquad (8)$$

The output contains a dc component, linear terms at α and β, second harmonics, and sum and difference frequencies. Second-order distortion is the ratio of the power at the sum and difference frequencies to the power at the fundamentals. By selecting a_1 and A, it is possible to compute a_2 for any desired amount of second-order distortion.

The input spectrum can now be entered into a data block, transformed to the time domain, and the calculations indicated by equation 6 performed. The result is a test signal that can be used directly to evaluate system performance. Fig. 6b illustrates a test signal of this type as it appears on a swept spectrum analyzer while being output by the DAC.

This example is also an excellent illustration of the potential speed advantage of digital signal analysis. The spectrum in Fig. 6b was taken with an analog spectrum analyzer over a 2-kHz sweep width with 3-Hz resolution. Approximately one-half hour was required for a single sweep. The same result, over a wider bandwidth, with equivalent resolution and dynamic range can be computed by the 5453A in approximately twelve seconds.

Telephone Channel Measurements

The testing of telephone circuits used for the transmission of high-speed data is a difficult problem. While many different types of voice-grade data channels are available, we will limit our discussion to two-point, private-line, four-wire circuits. Such a circuit
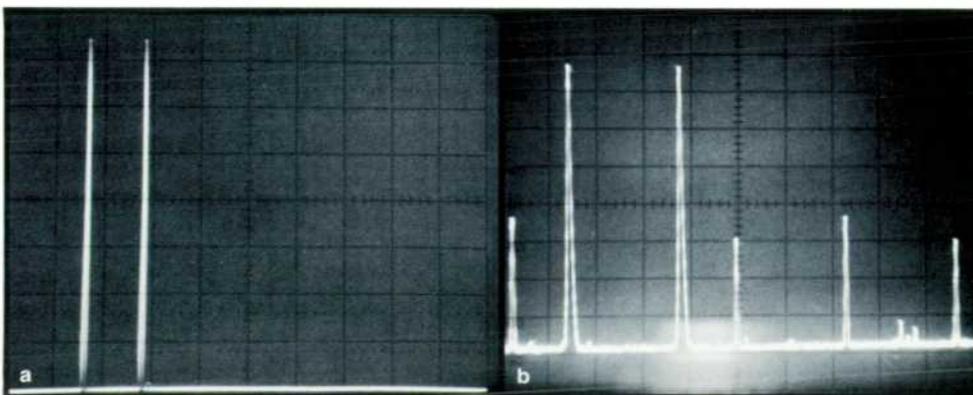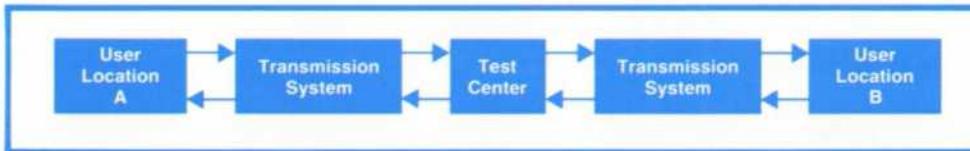

Fig. 6. *Spectrum of a typical stimulus signal for intermodulation distortion measurements (a), and the spectrum of a typical response (b). In this case the response signal was generated by the 5453A and contains a known amount of intermodulation distortion. It could be used to test a distortion-measuring system. Other known impairments are also easily generated.*

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Fig. 7. *Two-point private four-wire data circuits like this one can be measured in both directions from the test center by the 5453A. Circuits not passing through the test center can also be tested.*

might be laid out as shown in Fig. 7. Several transmission media may be used between intermediate points along the circuit, including PCM, FDM cable, and microwave systems. The user leases the circuit from a common carrier and it is available to him on a full-time basis.

Most transmission systems were originally designed to enable people to talk to people. As data traffic has increased in volume, speed, and importance, a number of circuit characteristics, most of which offer little or no degradation to voice traffic, have become significant. A list of the parameters presently measured on data circuits by the 5453A appears in Table I. The interested reader unfamiliar with the terminology will find additional information in references 3 and 4. The parameters encompass such fundamental characteristics as insertion loss, power, frequency, noise, distortion, and incidental modulation.

A circuit like that of Fig. 7 may be tested from end to end or between any two points at which voice-frequency access is available. Assume that a 5453A is located in the test center and that we wish to characterize the portion of the circuit from that office to user location B. The transmit and receive sides of the circuit could be connected together at the user location. This would form a loop and the line could be treated as a two-port network by the 5453A. However, this approach does not make it possible to separate the characteristics of the two sides of the circuit. Its major usefulness lies in the ability to characterize a known-good circuit on a looped basis and to save the result in the mass memory. Subsequent troubles may then be traced to either the circuit or the terminal equipment by repeating the measurement and detecting changes from the benchmark. This can normally be accomplished without dispatching a trained repairman to the remote location.

The 5468A Transponder has been developed to provide for two-way measurements between distant locations. When connected to the circuit at the user location, it can be commanded automatically from the 5453A to generate the test signals required for measurement of the receive line or to process signals generated by the 5453A in a manner that allows the transmit-line characteristics to be calculated (see box, page 16).

With the equipment in place, the operator requests any or all of the transmission parameter measurements listed in Table I. The 5453A will make all nine measurements in both directions on the circuit in approximately two minutes. Fig. 8 illustrates the data output.

Other capabilities of the program include storage, retrieval, and purging of test results in the mass memory. It is also possible to compare data to a benchmark or to specifications the circuit must meet. Data taken on two segments of a circuit may be combined to yield the overall characteristics. Operator interaction with the program is purely conversational, allowing him to accomplish complex tasks rapidly with a minimum amount of training.

Other Applications

The 5453A is not limited to testing installed communication channels. The same approach could be applied equally well, for example, to end-to-end checkout of a complete communications system on the production floor. The speed of digital techniques makes it feasible to do 100% testing and have complete records even for high-capacity systems.

Additional 5453A applications are to be found in the design and testing of all types of communications equipment, such as data sets, facsimile transceivers, equalizers, multiplex-channel modems, telephone sets, and loop extenders.

Correction

In our April 1975 issue, page 10, it is stated that Model 5308A time-interval measurements "are guaranteed accurate within one nanosecond." That sentence should have read, "Measurements are guaranteed accurate within five nanoseconds and are typically accurate within one nanosecond." The editors apologize for losing a crucial line of type.

```
DATA ID :A-0231 .23JAN75     .VUI NYC TO SFO
    TRANSMISSION            TRANSMIT        RECEIVE
       RECORD        FREQ   DELAY   LOSS   DELAY   LOSS
                     250    3230    1.9    3150    2.3
                     500    950     -.7    980     -.6
                     750    480     -.5    470     -.6
                     1000   180     .0     190     .0
                     1250   70      .1     100     .2
                     1500   40      .2     50      .4
                     1750   0       .4     0       .9
                     2000   -10     .9     -30     1.7
                     2250   -40     1.5    -30     2.4
                     2500   0       2.1    0       3.1
                     2750   70      2.4    70      3.5
                     3000   170     2.7    200     4.1
                     3250   360     2.8    410     4.9
  1 KHZ LOSS      DB         -2.7           -3.0
  FREQ SHIFT      HZ         -.3            .3
  PHASE JITTER    DEG        4.8            3.1
  I-MOD DIST (2ND/3RD)DB    -42.0 /-42.9   -49.6 /-48.7
  FLAT  NOISE T/NT  DBRNO    49.1 / 50.2    48.1 / 47.8
  C-MSG NOISE T/NT  DBRNCO   46.1 / 48.2    45.7 / 45.4
  INTERFERING TONE   :  937. HZ  -41. DBM
```

Fig. 8. *5453A TPA printout of data-circuit test results. Nine tests are made in less than two minutes.*

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Portable Transponder Allows
Two-Way Data Channel Measurements

When used with the 5453A Transmission Parameter Analyzer (TPA), the HP 5468A Transponder, Fig. 1, provides the capability to characterize four-wire voice-grade facilities automatically in both directions of transmission. Control of the transponder is by means of coded command tones generated by the TPA. The transponder provides the test signals needed to characterize the receive line and conditions test signals received from the TPA so the system can compute the transmit line characteristics. The automatic feature can be overriden, allowing manual measurements of received level and noise without tying up the TPA.

Fig. 1. *5468A Transponder works with 5453A Transmission Parameter Analyzer to characterize transmit and receive lines of data circuits.*

Three test signals are provided by the transponder to characterize the receive line. A pure 1015.625-Hz holding tone is used to measure frequency shift, phase jitter, noise with tone, and 1-kHz loss. Intermodulation distortion requires at least two tones, and a third tone is added at ¼ power to better simulate an actual data signal. Attenuation and envelope delay distortion are measured using a broadband signal containing 16 tone pairs. The transponder also provides a 600-ohm termination on the receive line for no-tone noise measurements.

The 1015.625-Hz tone must have low incidental phase modulation (<0.1°), stable amplitude (<0.05 dB drift), and an accurate frequency (±0.025 Hz). The frequency accuracy requirement implied that a crystal was necessary, while the low phase modulation requirement ruled out a phase-lock loop. The approach taken in the transponder is to use a transversal filter to convert a stable digital clock into a sine wave with the desired characteristics. The circuit is illustrated in Fig. 2. Second-order distortion of less than 70 dB is typical of such a filter.

Three transversal filters are used to generate the intermodulation distortion test signal. The three frequencies are 703, 1172, and 1218 Hz.

The third test signal contains 16 pairs of sidebands spaced ±78 Hz about suppressed carriers spaced 250 Hz apart. Amplitudes and relative phase differences must be stable and uniform from one transponder to another. The 78-Hz modulation signal is generated using the transversal filter approach. The carriers are generated using a 63-clock-period (4 ms total
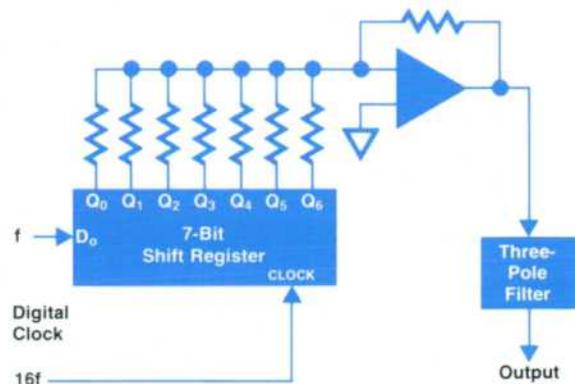
Fig. 2. *Transversal filters are used in the transponder to generate low-distortion test signals.*

length) pseudorandom binary sequence. The final output signal is then obtained by multiplication using the circuit shown in Fig. 3.

For measurements on the transmit line command tones are sent from the TPA to program the transponder into its signal-conditioning modes of operation. Attenuation and envelope delay distortion are measured by causing the transponder to provide an equal-level loopback. The characteristics of the transponder and the receive line are then subtracted from the measurement of the entire loop.

Measurement of noise with tone on the transmit line is accomplished by first passing the received signal through a 20-dB notch filter. With the tone reduced in amplitude by 20 dB, the entire spectrum (noise plus tone) is given 20 dB of gain before being looped back on the receive line. Thus noise on the receive line has a negligible effect on the measurement. The TPA removes the weighting effect of the receive line.

The measurement of intermodulation distortion is achieved by notching out the 703-Hz tone prior to loopback. Therefore, while harmonic distortion products may be formed as a result of transmission over the receive line, there are no intermodulation products. Once again, the previously measured frequency response of the receive line is used by the TPA to compute distortion.
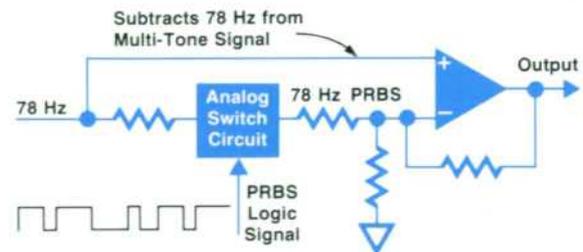
Fig. 3. *Test signal for envelope delay distortion and attenuaton measurements is generated by multiplying a 78-Hz signal by a pseudorandom binary sequence (PRBS).*

Acknowledgments

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HP Model 5453A Transmission Parameter Analyzer

Contact the factory or your local Hewlett-Packard sales office for specifications.
PRICES IN U.S.A.:
  5453A Transmission Parameter Analyzer, $62,800.
  5468A Transponder, $2500.
MANUFACTURING DIVISION: SANTA CLARA DIVISION
    5301 Stevens Creek Boulevard
    Santa Clara, California 95050 U.S.A.

Roger F. Rauskolb

Roger Rauskolb, a native of Maehrisch-Ostrava, Czechoslovakia, received his Dipl. Ing. degree from the Technische Hochschule of Darmstadt, Germany, in 1961. His career at HP has been a varied one that began in 1962 and includes service as a microwave project engineer, spectrometer project manager, digital signal analysis (and 5453A) group leader, and now, member of the HP Laboratories technical staff. In 1965 he received his MSEE degree from Stanford University. A resident of Palo Alto, California, Roger is married and has two daughters. He's an audiophile, a photographer, a swimmer, and a skier. His interest in building a better world goes back many years and currently expresses itself in his membership in Project Survival, a group concerned with energy problems and education for long-term survival on earth.

Hewlett-Packard Instruments for Checking Voice-Grade Telephone Lines

The August 1974 issue of the Hewlett-Packard Journal contained a chart comparing the capabilities of six Hewlett-Packard instruments designed to measure various parameters of voice-grade telephone channels used for data transmission. All of these instruments have now been described in the Hewlett-Packard Journal. The instruments, and the issues in which they appear are:

CCITT Standards
  3552A Transmission Test Set (May 1975)
  3770A Amplitude/Delay Distortion Analyzer (November 1974)
  3581C Selective Voltmeter (Related to 3580A Spectrum Analyzer, described in September 1973)

North American Standards
  3551A Transmission Test Set (May 1975)
  4940A Transmission Impairment Measuring Set (August 1974)
  5453A Transmission Parameter Analyzer with 5468A Transponder (May 1975)
  3581C Selective Voltmeter (see above)

Robert H. Perdriau

Bob Perdriau is product marketing engineer for digital signal analyzers at HP's Santa Clara Division. Before assuming that post in 1973 he had served as a design engineer and as an applications engineer for three HP divisions. Born in Boston, Massachusetts, he graduated from the University of Massachusetts in 1963 with a BSEE degree. Except for three years in the U.S. Army, he's been with HP ever since. Bob is married, has two children, and lives in Los Altos, California, where for the last two years he's been busy building a major addition to his home. With that project about finished, he's looking forward to having more time for his other interests, which include fishing and hunting, woodworking, and bicycling.

Stephan G. Cline

Now a laser interferometer applications engineer, Steve Cline until recently was involved in Fourier analyzer hardware and software design. With HP since 1968, he wrote much of the software for the 5450A Fourier Analyzer, helped design the 5470A Fast Fourier Processor, and served as project leader for the 5471A FFT Arithmetic Unit and the 5468A Transponder. Born in Camp McCoy, Wisconsin, he received his BSEE degree from Michigan State University in 1967 and his MSEE degree from Stanford University in 1968. Especially interested in meeting people from different cultures, Steve enjoys travelling and serves as treasurer of American Field Service, a foreign-student exchange program. His main recreational activity is golf, but he enjoys biking, too. He and his wife live in Los Gatos, California.

A Precision Spectrum Analyzer for the 10-Hz-to-13-MHz Range

Adaptable to automatic systems or bench use, a new spectrum analyzer has measurement resolution of 0.01 dB, passbands as narrow as 3 Hz, and a dynamic range of 70 dB.

by Jerry W. Daniels and Robert L. Atchley

THE SPECTRUM ANALYZER and the network analyzer are assuming greater and greater importance as means of evaluating the performance of electronic circuits and devices. The network analyzer gives complete information about the amplitude and phase performance of linear networks while the spectrum analyzer evaluates the amplitude performance of both linear and nonlinear networks.

The spectrum analyzer is a single-channel instrument that selects and measures the amplitudes of the individual frequencies that make up a complex signal. It is thus able to detect and measure the distortion and intermodulation products of nonlinear networks.

The network analyzer is a dual-channel instrument that compares the amplitudes and phases of two signals, usually the input and output of a network or device. It is normally not suitable for measurements involving nonlinear networks because it is designed on the assumption that only one frequency at a time will be at its input. The method of heterodyning signals within the network analyzer could cause spurious responses if the input signal were distorted or otherwise contained more than one frequency.

A New Spectrum Analyzer

Some two years ago, a network analyzer for measuring the magnitude and phase characteristics of signals in linear networks over a frequency range of 50 Hz to 13 MHz was introduced (Model 3570A).[1] The accuracy and ready adaptability of this instrument to systems use have now been incorporated in a new spectrum analyzer, Model 3571A, for measurements of complex signals over this same frequency range (and down to 10 Hz). This new instrument (Fig. 1) performs waveform signal analysis with full assurance that all internally-generated image and inter-

modulation responses are below the measurement range of the instrument.

The new spectrum analyzer has accuracy and precision normally not associated with spectrum analyzers. It has an amplitude resolution of 0.01 dB, an accuracy of ± 0.05 to ± 1.15 dB, depending on the signal level and frequency, a dynamic range of 70 dB and a measurement range of 150 dB. The analyzer's passband is selectable in steps from 10 kHz down to 3 Hz, the stability of both the analyzer and the synthesizer used as the local oscillator being such that the 3-Hz bandwidth is practical even at 13 MHz. The frequency of a signal component can be determined well within 1 Hz. Typical measurement results are shown in Fig. 2.

Some of the measurements for which this high-precision instrument is especially useful are harmonic and intermodulation distortion in amplifiers, power-line sidebands and harmonic levels in oscillators, RF and LO feedthrough in mixers, and frequency translation errors in communications repeaters. It can also serve as a frequency-response test set for high-precision measurements, such as amplitude errors in the up-converted channels of multiplex communications systems.

Remote Control

Besides being operable from the front panel, the new spectrum analyzer is also programmable through the HP Interface Bus.[2] Every front-panel switch position (except for the ON/OFF switch) is assigned an ASCII code so it can be selected by a system controller. The analyzer can thus be incorporated into calculator-controlled automatic measurement systems (Fig. 3) that can manipulate the data so it can be presented in more meaningful form. For example, it can function as a high-precision distortion analyzer by providing a mathematically exact sum-

Fig. 1. *Model 3571A Tracking Spectrum Analyzer (lower unit) works over a 10-Hz-to-13-MHz range using one of the HP synthesizers (upper unit) as a local oscillator. The combination of analyzer and synthesizer is known as the Model 3044A Spectrum Analyzer.*

mation of the individually-measured distortion products. An automatic system not only speeds measurements, removes the tedium from repetitive measurements, and facilitates a high degree of data manipulation, but it also provides a means for enhancing measurement accuracy by using calibration routines to store the results of reference measurements and then using these to correct actual measurements.

Information Display

To obtain the high resolution that the accuracy of this instrument makes possible, it has a digital readout rather than the CRT display commonly associated with spectrum analyzers (however it has an analog output for a CRT display). Superficially it resembles the traditional wave analyzer more than a

spectrum analyzer but it differs in the characteristics of its selective filters, which have a rounded response curve that minimizes ringing during a frequency sweep, rather than the wave analyzer's squared-off response curve.

Because the front-panel of the new Model 3571A Tracking Spectrum Analyzer resembles neither the traditional spectrum analyzer nor a wave analyzer, a look at the controls can be informative. First of all, there is no tuning control on the instrument itself. It was designed to work with the offset frequency signal from either the HP Model 3320A/B Frequency Synthesizer or the Model 3330A/B Automatic Frequency Synthesizer. Tuning the synthesizer tunes the analyzer, the frequency of the synthesizer corresponding to the center frequency of the analyzer's
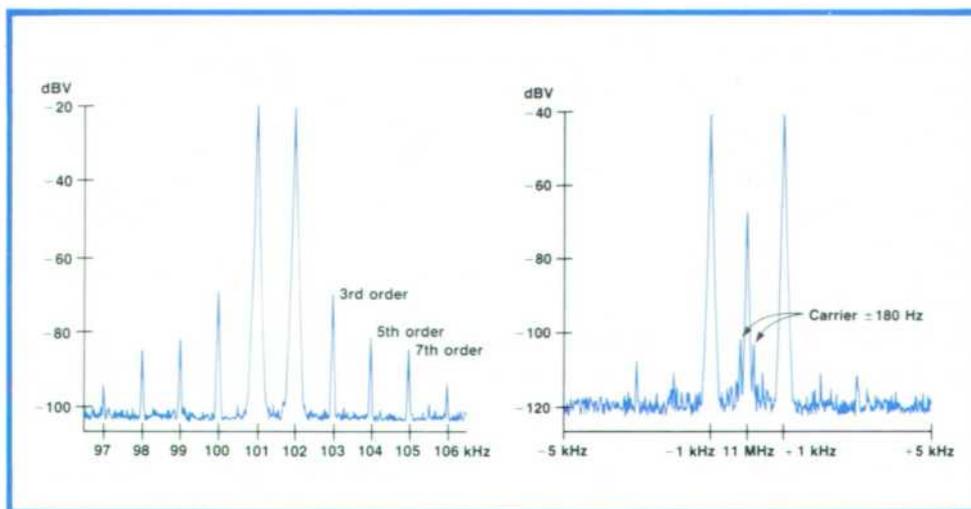
Fig. 2. *Typical spectra recorded by a 3045A calculator-controlled spectrum analyzer system based on the Model 3571A Tracking Spectrum Analyzer. The recording at far left was made during a two-tone intermodulation test of an amplifier using input frequencies of 101 and 102 kHz. The odd-order intermodulation products are clearly shown. The recording at near left shows the output of a double-balanced mixer fed by a high-level 11-MHz carrier through the LO port and a mixture of 1-kHz and low-level 180-Hz tones through the RF port. The up-converted 180-Hz signal is clearly resolved about the 11-MHz carrier.*

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Fig. 3. *The Model 3571A Tracking Spectrum Analyzer also functions under programmable calculator control through the HP Interface Bus, giving an automatic measurement and data-reducing system that shortens test time and decreases the possibility of measurement error. A packaged calculator-based system that includes the analyzer is known as the Model 3045A Automatic Spectrum Analyzer.*

passband (it is for this reason that it is known as a Tracking Spectrum Analyzer).

The controls that are on the analyzer have to do with bandwidth, signal level, units of measurement in the display, and input impedance. The input impedance is selectable to allow use of the analyzer in a variety of measurement situations. The 50Ω and 75Ω input impedances match a wide range of high-frequency devices and are especially useful for measurements in communications systems. The 1MΩ input impedance allows the user to supply his own termination for other impedance levels, and it also allows a conventional oscilloscope probe to be used for high-impedance circuit probing.

Full-scale input amplitude ranges are from 3.16V rms to 1 mV rms in eight 10-dB steps with a full 70-dB dynamic range on each step. An OVERLOAD indicator flashes if the signal exceeds the input range.

As mentioned earlier, the passband is selectable from 3 Hz to 10 kHz in a 1-3-10 sequence. The wider passbands permit relatively fast sweeps over a wide band for a quick, overall look at a spectrum. The narrow passbands make it possible to isolate low-level

frequency components from stronger frequencies close by. Because of the stability of the instrument, two signals only 15 Hz apart but with an amplitude difference of 55 dB can be resolved. Line-related sidebands more than 70 dB down can be resolved.

Measurement results may be displayed in a variety of measurement units. With the DISPLAY REFERENCE switch in the dBV position, the display reads dB with respect to 1 volt no matter what the input impedance may be. With the switch in the dBm position, the instrument displays the measured power in the selected input impedance (either 50Ω, 75Ω, or an external 600Ω). With the switch in the RELATIVE position the instrument displays a dB reading relative to a previously established reference. For example, a reading in either the dBV or dBm position can be stored as a reference by pressing the ENTER OFFSET button, establishing this signal level as the 0.00 dB level. Then with the switch moved to the RELATIVE position, all further readings are displayed as so many dB above or below this reference. This is handy for reading the level of harmonics with respect to the fundamental.

This arrangement also allows the user to calibrate the instrument with respect to some other impedance level. With an external termination of the desired impedance attached, the user supplies a known 0-dBm signal and presses the ENTER OFFSET button. Subsequent measurements made with the switch in the RELATIVE position will then be direct reading in terms of this impedance level.

The analog equivalent of the stored reference is subtracted from the analog output voltage allowing expanded-scale visualization of a portion of the spectrum on a CRT display or X-Y recording.

Block Diagram Overview

As other spectrum/wave analyzers do, the Model 3571A heterodynes the input signal to an intermediate frequency for narrowband filtering. A block diagram is shown in Fig. 4. The input signal is mixed with the synthesizer offset frequency to derive a 20-MHz intermediate frequency (the synthesizer offset frequency is precisely 20 MHz higher than the synthesizer main output). The up-conversion to 20 MHz places the image frequencies in a range of 40 to 53 MHz, which are easily attenuated more than 80 dB by a low-pass filter at the input.

The 20-MHz output of the mixer is filtered to remove unwanted mixer products and then down-converted to 100 kHz for the filtering that establishes the instrument's passband. An IF of 100 kHz was chosen to permit the use of narrow-band crystal filters.

The filtered IF is then processed by an amplifier whose output is logarithmically proportional to the input. This amplifier, a hybrid IC similar to that used
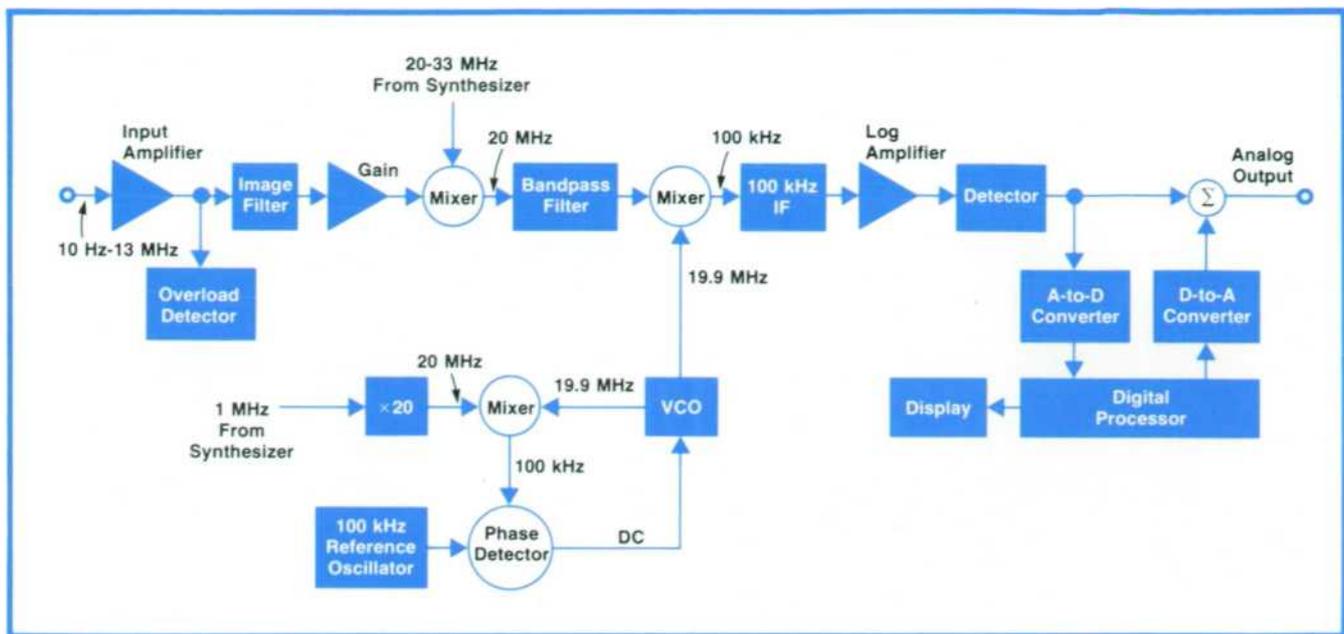
Fig. 4. *Simplified block diagram of the Model 3571A Tracking Spectrum Analyzer.*

in other HP instruments,[3] converts the signal voltage level to the equivalent dB level by compressing signals in proportion to their amplitude.

The detector is a peak-to-peak type. The detector output, a dc voltage proportional to the log of the signal amplitude, is smoothed in a low-pass filter and then provided at a rear-panel connector as a Y-axis output for use by a CRT display or by an X-Y plotter (an X-axis output is available from the associated synthesizer). A front-panel switch can slow the filter response by a factor of 20 to smooth noisy signals.

The detector output is also converted to an equivalent digital number by an analog-to-digital converter and sent to the digital processor. The number is processed in accordance with the format established by the settings of the front-panel switches. Offset, dB, dBV, dBm 50Ω, dBm 75Ω, dBm 600Ω, and input range all affect the number that is finally displayed.

The difference between the displayed number and the raw digitized number is converted to an analog voltage and applied as an offset to the rear-panel analog output voltage. The analog output is thus consistent with the digital readout in terms of measurement units (0.1 V = 1 dB).

Analog Circuit Details

Now to examine some of the considerations involved in the design of this instrument. The dynamic range of a spectrum analyzer is limited by noise at the low end and intermodulation distortion at the high end. The design of the input circuits is directed towards maximizing the difference between these two extremes.

Low noise is achieved by use of a J-FET buffer am-

plifier which also gives high input impedance. The use of the complementary-symmetry configuration obtains high linearity and very good frequency response. By making the "straight-through" input range 10 mV rms, the noise level allows the desired 70-dB range to be obtained with the widest bandwidth (10 kHz).

The output of the input amplifier is monitored by the overload detector, a peak detector driven by an amplifier that has greater than 60-MHz bandwidth to enable response to out-of-band signals. As long as the front-panel overload indicator is not illuminated, the user is assured that the input signal is within the linear range of the amplifiers, which means that internally generated distortion and intermodulation products are more than 80 dB below the full-scale input range.

Only Two Conversions

The frequency conversion to 20 MHz occurs in an active double-balanced mixer. After bandpass filtering, the 20-MHz signal is presented to the second mixer for conversion down to 100 kHz. The second mixer's local oscillator frequency (19.9 MHz) is phase-locked to a 1-MHz signal from the synthesizer and is thus in precise relationship to the first local oscillator frequency.

Since the 100-kHz IF is derived by mixing a 20-MHz signal with 19.9 MHz, a 19.8-MHz signal in the first IF channel would also be converted to 100 kHz. Normally, this situation would be avoided by having another IF conversion between the 20-MHz and 100-kHz IF's. Fortunately, we were able to avoid the extra cost of a third IF channel, not to mention the ad-

Attenuating the Classical Attenuator Problem

The classical attenuator problem is encountered anytime a device under test is placed between a single-ended source and a single-ended detector. It may manifest itself in several ways:

- Apparent detector inaccuracies at low signal levels;
- Reduction of dynamic range at low frequencies;
- Spurious responses caused by common-mode signals.

The basics of the problem are outlined in the drawing. This represents a signal source driving an attenuator that is monitored by a detector. Coaxial cables are used, and the test is being conducted at frequencies in the audio range (at high frequencies, the coaxial cables behave more like baluns and the problem is not so acute).

To simplify the discussion, the attenuator is set for infinite attenuation. It is easily seen that return currents through the cable shield to the signal source can develop a voltage, e_a, across the finite resistance of the cable shield, R_{c1}. This causes voltages across R_{c2} and Z.

If the detector input resistance, R_D, is high, the voltage drop across R_{c2} is seen by the detector, so a residual signal is measured even with infinite attenuation.

When $(R_{L2} + R_D) >> R_{c2}$,

$$e_a = \frac{R_{c1}(R_{c2} + Z)}{(R_s + R_{L1})(R_{c1} + R_{c2} + Z) + R_{c1}(R_{c2} + Z)} e_s$$

and,

$$e_D = \frac{R_{c2}}{R_{c2} + Z} e_a$$

The object is to reduce the detector signal, e_D, to zero, or at least to insignificant proportions. This would occur if either R_{c1} or R_{c2} were zero, but this would be difficult to achieve. Increasing $(R_s + R_{L1})$ and/or Z would also reduce e_D but R_s and R_{L1} are fixed by the measuring system, which leaves Z as the only variable available for manipulation.

From the figure it is easily seen that if Z were zero, which means that the source and detector would be referenced to the same ground, the full voltage of e_s would be measured by the detector. Consider a 50Ω system using two 4-foot lengths of RG/58U cable with an infinite attenuator between. What would be the real attenuation?

$R_{c1} = R_{c2} = 20\ m\Omega$ and $R_s + R_{L1} = 100\Omega$. If Z were equal to zero, then:

$$\frac{e_D}{e_s} \approx \frac{(20 \times 10^{-3})(20 \times 10^{-3})}{100(40 \times 10^{-3})} \longrightarrow -80\ dB$$

Increasing Z to 1Ω yields:

$$\frac{e_D}{e_s} \approx \frac{(20 \times 10^{-3})(20 \times 10^{-3})}{100(1.0004)} \longrightarrow -108\ dB$$

thus, a small increase in Z results in a significant reduction in e_D. A similar analysis shows that common-mode voltages caused by ground loops are also reduced by increasing Z.

Increasing Z, however, would not allow the barrel of the front-panel BNC connector, which is connected to signal ground, to be tied directly to earth ground. The classical attenuator error was reduced in the Model 3571A without fully floating the input connector by making Z a saturable-core inductor wound with #17 wire. This has practically zero impedance at dc but a finite impedance at frequencies where the classical attenuator problem exists. On the other hand a large powerline signal through Z, such as might occur with a grounding error, would saturate the core, reducing the impedance of Z to less than one ohm. This is why the input to the Model 3571A is not described as "floating", but as "isolated at low frequencies".

The potential reduction in measurement errors achieved by this arrangement is shown by the graph below. This was made by the Model 3571A measuring the output of a 120-dB attenuator fed by a one-volt signal supplied through a 4-foot cable (bandwidth: 3 Hz; range: 1 mV; smoothing: on).
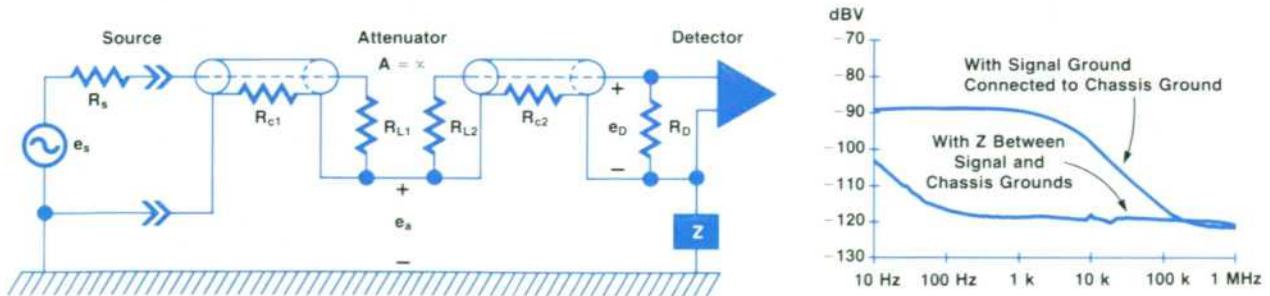
ditional problems with intermodulation and noise that another mixer would introduce, by use of a 20-MHz filter that attenuates 19.8 MHz more than 80 dB.

The 20-MHz filter consists of two cascaded two-pole crystal filters, one of which is shown in Fig. 5. Stagger-tuning the crystals gives a bandwidth of 30 kHz. However, at 19.8 MHz the currents through the

shunt capacitances of the two crystals are exactly equal and of opposite phase, cancelling at point A and giving a transmission zero at 19.8 MHz. Signals at 19.8 MHz are attenuated more than 50 dB in each stage, more than adequate to meet demands.

IF Stability

The 100-kHz IF is where all of the bandwidth selec-

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tion and most of the gain occurs. The filters are all 5-pole synchronously-tuned types with a −3dB to −60dB shape factor of 10. The response curve is approximately Gaussian. The three widest passbands are derived from high-Q LC tanks while the rest are crystal derived. A single set of five crystals is used with loading resistors to broaden the bandwidth when required.

Frequency drift in narrowband filters can cause problems. When using the 3-Hz bandwidth, a drift of 1 Hz, although only 0.001% at 100 kHz, would cause significant measurement errors. This problem was minimized by incorporating a 100-kHz oscillator in the 19.9-MHz phase-locked local oscillator circuit (Fig. 4). The 100-kHz crystal of this oscillator is the same type used for the IF filters; in fact, all six crystals are supplied as a matched set. Therefore, any drift in the IF center frequency is matched by a compensating drift in the local oscillator.

Digital System Details

The digital machine in the 3571A is a 16-bit binary serial processor using 8K of ROM. It has four major functions: the measurement routine, the data entry, the data output, and the calculation of the analog output.

The measurement routine is the data gathering process. Here the controller commands the analog-to-digital converter to digitize the output of the log amplifier. The output of the digitizer is then manipulated according to the program in the program storage (PS) register. The controller does this by interrogating the "PS" register and checking to see what amplitude range is in use. It then subtracts or adds a number to correct the reading to dBV (1V = 0dBV).

The controller now must check to see if the answer is to be displayed in dBV, dBm, or dB relative to a stored number. If it is to be displayed in dBV, it continues with the binary-to-BCD conversion for display. If the displayed answer is to be in dB relative to some reference, this reference, which was stored in memory by the data routine, is subtracted from the dBV answer. If the program calls for a dBm display, the controller again corrects the dBV answer by the appropriate factor for the selected terminating impedance (50Ω, 75Ω, or 600Ω).

In any case the binary answer must be converted to BCD for display purposes. This is done by hardware. The binary data is shifted into a binary-to-decimal converter with the most significant bits first. At the end of the shifting a BCD answer is stored in the register and is latched into the displays. It may also be output to the HP interface bus (HP-IB).

The data entry routine is primarily used to bring in data from the HP-IB for remote control of the 3571A. The 3571A, except for the power switch, is complete-

ly programmable with all control executed through the PS register. During local control, the front-panel switches are parallel loaded into the PS register but under remote control the front-panel controls are locked out and the contents of the PS register may be changed only by data from the HP-IB.

Pushing the ENTER OFFSET switch during local control sets the data flag. The controller checks to see if it is in local control, and finding that it is, takes the present dBV reading, which has been stored in memory, and places it into memory as the reference for a relative dB display.

Data coming from the HP-IB is parallel loaded into the 8-bit input (I) register. The controller uses a qualifier to sense this condition and upon receiving this information it shifts the data serially through an optical isolator to the Q register for decoding (both the HP-IB input and HP-IB output circuitry are isolated from measurement ground). After the data has been deciphered, it may be used to program an arbitrary offset into memory, or to initiate some immediate command. It could also be recognized as an unused command and be ignored.

The controller also calculates an offset voltage to be subtracted from the log amp output so the analog output will correspond to the display. During the time that the controller is not in a measurement routine or data entry, the controller uses the digital-to-analog portions of the successive-approximation digitizer to construct an analog voltage. For a given display reference and input range, the number is constant so a follow-and-hold circuit can retain the analog voltage while the controller is occupied with the other routines. This analog signal is then added to the normal (straight through) analog output to obtain the required offset. Because only the offset is obtained by the D-to-A converter, small perturbations in the signal amplitude are transferred to the analog output signal. The resolution then is that of the log amplifier, rather than the digitizer.
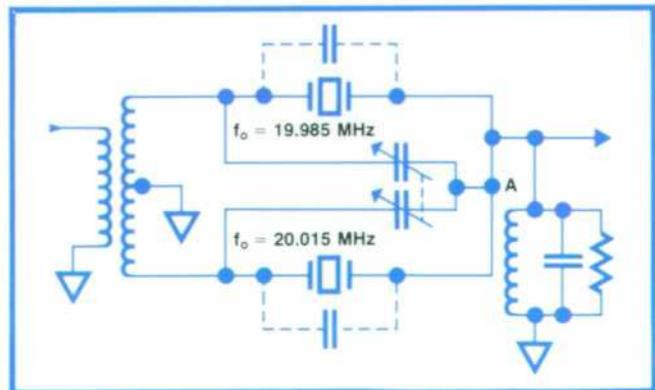

Fig. 5. *20-MHz IF filter precedes the second mixer. The adjustable capacitors balance the crystal distributed capacitance to achieve a zero at 19.8 MHz.*

Acknowledgments

Group Leader Paul Thomas was responsible for the basic block diagram and he contributed to the design of the log amplifier and the method of phase-locking to an external synthesizer. Howard Hilton was responsible for the input amplifier, overload detector, image filter, and 100-kHz reference oscillator. The 100-kHz IF was designed by Tom Rodine. Product design was by Jim Saar. Virgil Leenerts was responsible for the front-panel design and provided the low-frequency isolation scheme (see box, page 22). 🜨

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Robert L. Atchley

Bob Atchley joined Hewlett-Packard in 1968, going right to work on the Model 3570A Network Analyzer where he eventually assumed responsibility for the digital processor. He did the same for the Model 3571A Spectrum Analyzer. Married, and with two children, Bob once took his family to Bangkok, Thailand, (1967) to work on a study project for Colorado State University, where he had earned BSEE and MSEE degrees. Bob also dabbles in photography.

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