Errata

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HP References in this Application Note

This application note may contain references to HP or Hewlett-Packard. Please note that Hewlett-Packard's former test and measurement, semiconductor products and chemical analysis businesses are now part of Agilent Technologies. We have made no changes to this application note copy. The HP XXXX referred to in this document is now the Agilent XXXX. For example, model number HP8648A is now model number Agilent 8648A.

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A NEW TECHNIQUE FOR PULSED RF MEASUREMENTS

APPLICATION NOTE 120

5952-0533 Printed: SEP 1969

HEWLETT hp PACKARD

FOREWORD

This application note describes new techniques in the measurement of pulsed RF. By using a recently introduced Hewlett-Packard instrument, the 5360A Computing Counter, such measurements can now be made easier and with orders of magnitude greater accuracy and resolution than previously possible.

It is now not only possible to detect the existence of frequency perturbations during a pulsed RF burst, but also to measure them accurately. Furthermore, there is no duty cycle limitation; even a single burst of pulsed RF can be measured with no degradation in accuracy.

In short, the computing counter has made the impossible possible and the difficult easy in the measurement of pulsed RF.

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A NEW TECHNIQUE FOR PULSED RF MEASUREMENTS

MEASURING PULSED RF – PREVIOUS TECHNIQUES

The wavemeter has long been used to measure pulsed RF frequencies. But the accuracy of a good wavemeter is about 0.1%, and obviously the system requires a repetitive input which makes the wavemeter duty-cycle limited. The lowest PRF is about 100 Hz and the lowest input frequency that can be measured is about 1 GHz. Physical size of the wavemeter is the limitation here. Thus, provided the input frequency is above 1 GHz, the PRF not too low, and a maximum of 3 digits of information are required, the wavemeter offers a solution to pulsed RF measurements.

The transfer oscillator may also be used to measure pulsed RF frequencies. It does provide better accuracy and resolution than a wavemeter, but the major problem is error in tuning.

It takes considerable operator experience to minimize this error, especially at narrow pulse widths. The transfer oscillator can provide indications of frequency perturbations across the RF burst, but they have to be relatively large, particularly if a measurement of them is attempted. Again, operator skill in tuning the oscillator plays a significant part in the amount of information gained. Duty cycle limitation is, of course, the same as with the wavemeter.

Now, let's look at how the Computing Counter makes these measurements directly, with high accuracy, and with no duty cycle limitations.

THE 5360A COMPUTING COUNTER – A BRIEF RESUME

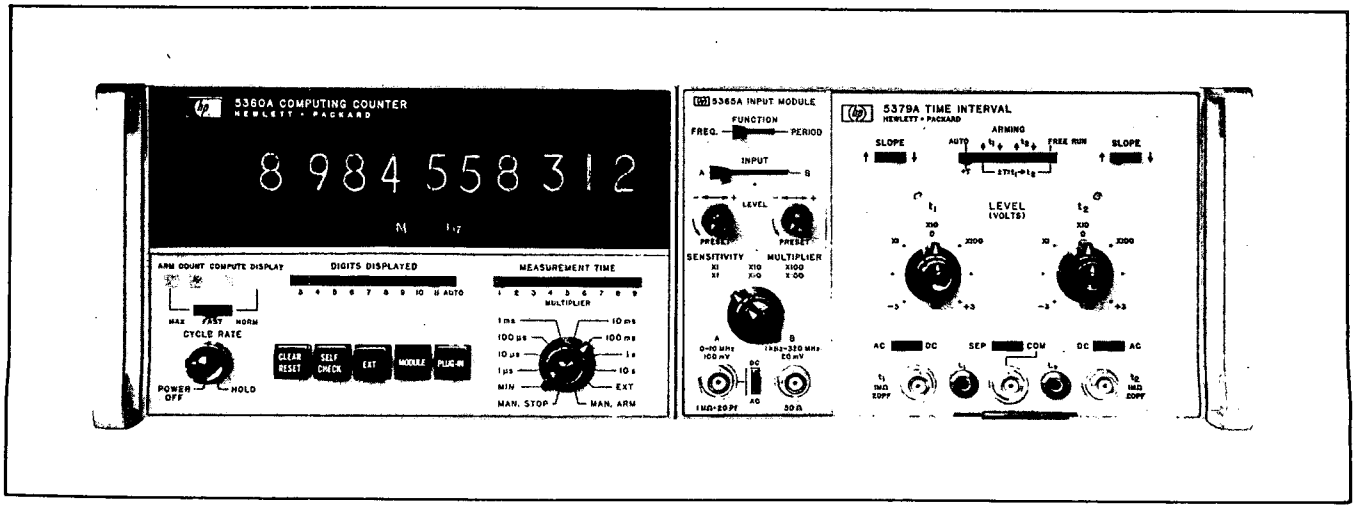
The Computing Counter is best described as a "general purpose, high precision digital instrument with built-in computational capability". It can certainly count, and does so more accurately, faster, and easier than any other frequency measuring device available. For example, any frequency from 1 Hz to 320 MHz can be measured in one second obtaining 10 digits of information to an absolute accuracy of 1×10^{-9}. Even accuracies of 1×10^{-3} can be obtained in 1 μsec, and with that measurement time over 300 measurements can be made in a second.

Frequency or period measurements are made through the 5365A Input Module. The low frequency input, Channel A, extends from .01 Hz to 10 MHz and has a 1 MΩ input impedance; the high frequency input, Channel B, is from 1 kHz to 320 MHz and has a 50Ω input impedance.

The Model 5379A Time Interval plug-in, shown in Figure 1, enables time interval measurements to be made to a resolution of 100 psecs, the time it takes light to travel about 1 inch! It can detect the fact that two events occurred simultaneously (i.e., a zero time interval) and even measure negative as well as positive time intervals. A negative measurement means that the input to t_2 of the 5379A occurred before the input to t_1.

A range of plug-in heterodyne converters is available to extend the frequency measurement capability to 18 GHz. They may also be used to measure pulsed RF with the Computing Counter as described later in this note.

Figure 1. The Hewlett-Packard 5360A Computing Counter



HOW THE 5360A COMPUTING COUNTER MEASURES PULSED RF

Three features allow direct, accurate measurement:

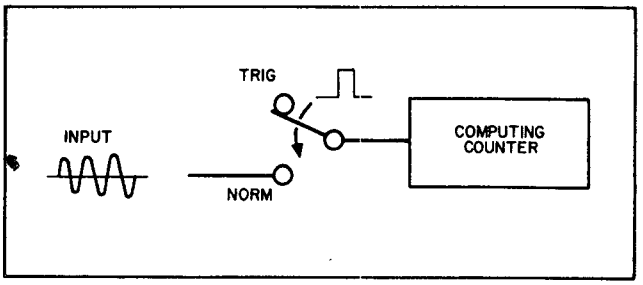
1. The counter may be triggered, either self or external.
2. Any measurement time is possible, e.g., 7 μsec.
3. The period count technique gives high accuracy. For example, 4 digits of frequency information are obtained in 1 μsec!

Triggered Measurements

The Computing Counter accurately measures the period of the input signal, rather than its frequency, by counting an internal clock for an integral number of periods of the input signal. (The reverse is the case, of course, for the conventional counter.) Frequency is computed and displayed from the digital data that results from the period measurement; hence, the name Computing Counter.

Among the many advantages of period counting is the fact that the counter's gate is synchronous with the input signal. This allows the user to begin a measurement at any desired point in real time. It is this facility that enables the direct measurement of pulsed RF. Figure 2 shows how it is done.

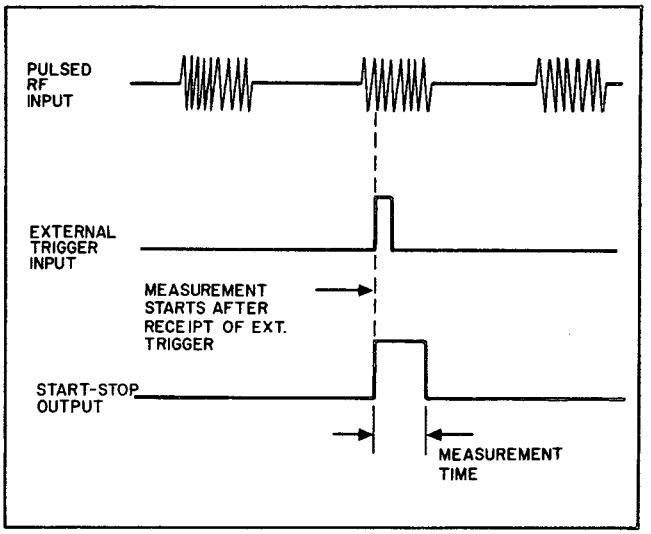
Figure 2. Triggered — Normal Operation of the Computing Counter



A measurement can not take place with the switch open, but the first cycle of the input signal that occurs after the switch is closed starts the measurement.

This switch does exist in the 5360A (the rear-panel TRIG-NORM switch). The switch is open in the TRIG position, but may be closed by applying a trigger pulse to the rear-panel EXTERNAL MEASUREMENT TIME input. Switch closure is referred to as "arming" the counter; i.e., internal circuitry readies the instrument to accept a measurement. Neither the waveform nor the timing of the trigger pulse affects the accuracy of the count. Arming occurs within 100 nsec after receipt of the leading edge of the trigger pulse. By triggering the counter "on" while a pulsed RF burst is present, a direct measurement of the pulsed RF frequency is initiated. This is summarized by Figure 3.

Figure 3. Timing Relationships of a Triggered Measurement



This triggered mode of operation is not possible with the conventional counter because the gate is not synchronous with the input signal. It is not possible, therefore, to directly and accurately measure the frequency of anything but a CW signal with the conventional counter.

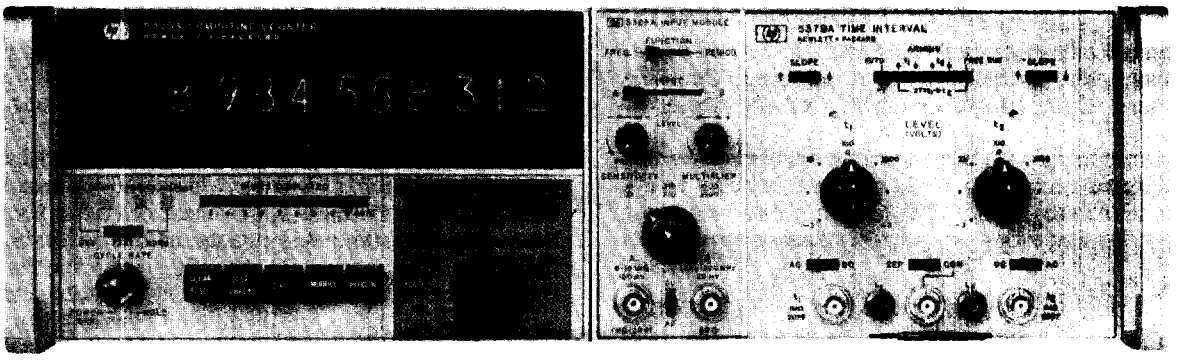
Note that the counter can be armed automatically by returning the TRIG-NORM switch to NORM. This mode of operation is usually used for CW frequency measurements where there is no requirement to start a measurement at any particular point in real time. Under certain circumstances this normal or non-triggered mode of operation can also be used to measure pulsed RF frequencies by the self triggering method discussed later in this note.

Measurement Time

The START-STOP output, available from a rear-panel BNC on the Computing Counter, is shown in Figure 3. The width of this pulse, which is equal to the measurement time, is determined by the front-panel MEASUREMENT TIME controls of the Computing Counter. These controls, shown in Figure 4, are much more versatile than those of a conventional counter. Similar to most conventional counters, MEASUREMENT TIME is adjustable in decade steps from 1 μsec to 10 seconds. Not found on the conventional counter, however, is the MULTIPLIER slide switch which is adjustable in integral steps from 1 to 9. MEASUREMENT TIME is equal to the time base setting multiplied by the MULTIPLIER slide switch setting. For example:

with the time base at 1 msec and MULTIPLIER at 4, MEASUREMENT TIME = 4 msec.

Figure 4. Measurement Time Controls of the 5360A Computing Counter



Because a longer measurement time gives greater accuracy, maximum accuracy is obtained by adjusting the MEASUREMENT TIME controls to cover as much of the pulse as possible.

Since the Computing Counter measures period, the measurement time is always an integral number of cycles of the input signal. Actual measurement time is completed with the first input cycle that occurs after the time set by the MEASUREMENT TIME switches. As an extreme example, with MEASUREMENT TIME at 10 msec and an input signal with 9 msec period, the actual measurement time is 18 msec.

With MEASUREMENT TIME set to MIN, a measurement is made over just one cycle of the input to Channel A or 32 cycles of the input to Channel B. This position is used to measure very short pulsed RF bursts as described in the Minimum Pulse Width section of this note.

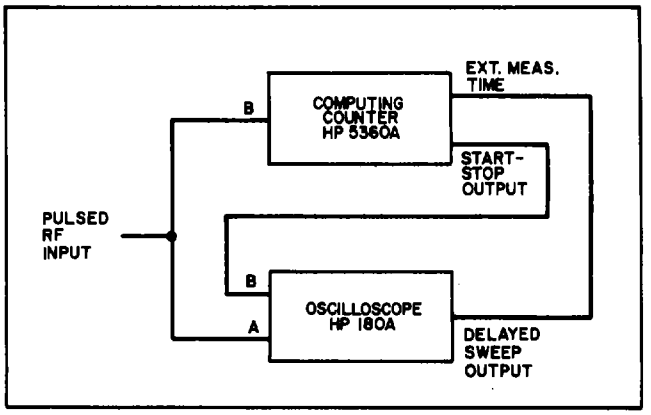
An EXT MEASUREMENT TIME position is also provided. In this mode the measurement time is determined by the width of a pulse applied to the rear-panel EXT MEASUREMENT TIME BNC. Thus, the measurement time is analog programmable in this mode, and times like 33.3 μsecs, for example, may be used.

.01 Hz to 320 MHz Pulsed RF Measurements

Pulsed RF measurements are easily made with the Computing Counter. Simply connect the signal to Channel A (.01 Hz to 10 MHz) or Channel B (1 KHz to 320 MHz) of the 5365A Input Module, and trigger the counter "on" when the pulse burst is present. Set MEASUREMENT TIME so that measurement is complete before the RF burst ends.

A convenient method to generate the trigger is to use an HP 180A Oscilloscope with 1821A or 1822A delayed sweep plug-in. Connect the signal to both counter and oscilloscope (see Figure 5). Set DELAYED SWEEP TRIGGER to AUTO and SPEED to about 100 nsec/cm. The delayed sweep is now firing as evidenced by the intensified dot on the trace. A DELAYED SWEEP OUTPUT trigger, that occurs at the same point as the intensified dot, is available from a rear-panel BNC on the 180A. Connect this output to the EXT MEASUREMENT TIME input on the Computing Counter rear panel, and move the TRIG-NORM switch to TRIG. The Computing Counter is now being armed at the same point as the intensified dot on the oscilloscope. Simply move the intensified dot with the DELAY dial to the desired measurement starting point on the RF burst.

Figure 5. Using the HP 180A Oscilloscope and the Computing Counter to Measure Pulsed RF

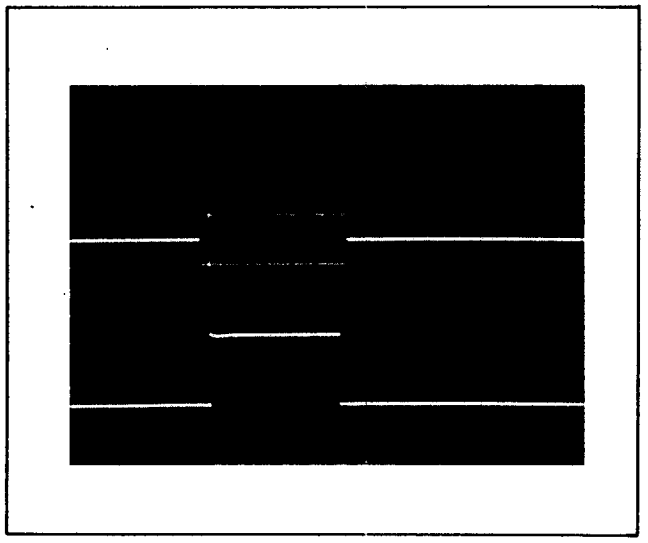


With the starting point of the measurement defined, the maximum allowable measurement time (which is to the end of the pulse burst) is readily found. Increase measurement time until the counter display disintegrates. This is immediately obvious and occurs because a measurement is attempted over a portion of the input where there is no signal. Now shorten measurement time until the display becomes stable. This is the maximum measurement time possible for the associated input signal.

Measurement time is also defined by an output available from the START-STOP connector on the Computing Counter rear panel. This is an extremely

useful output that shows not only where the measurement is taking place but how long it is. Use of this output is shown in Figure 6. Note the intensified portion of the RF trace; this is where the counter is being triggered to start the measurement.

Figure 6. Using the START-STOP Output
Upper Trace: Pulsed RF input to Computing Counter
Lower Trace: Computing Counter START-STOP output



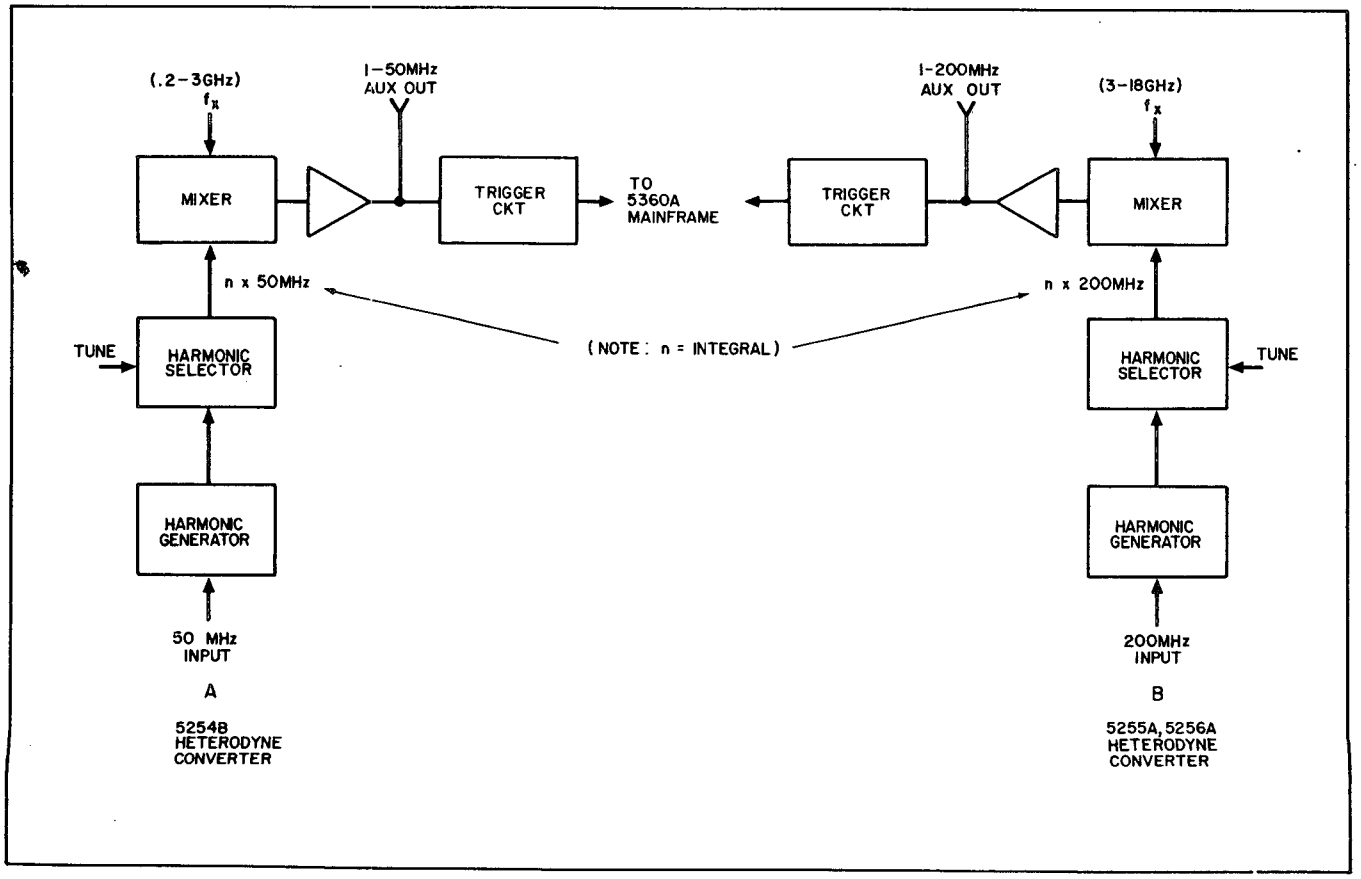
If the input frequency is too high for the oscilloscope, use a detector and display the detected output on the oscilloscope rather than the signal itself.

INCREASING THE FREQUENCY RANGE WITH HETERODYNE CONVERTERS

A range of heterodyne converters, specifically designed for the 5245L class of counters, may also be used with the Computing Counter. These converters extend the CW frequency range of either the 5245L or the Computing Counter to 18 GHz. With the Computing Counter only, these converters can also measure pulsed RF in the same frequency range. The 10536A Adapter must be used to provide mechanical compatibility as well as the appropriate program for the computing counter's arithmetic unit.

The three available converters fall into two classes as far as pulsed RF measurements are concerned. The 5254B (200 MHz - 3 GHz) forms one class; the 5255A (3 GHz - 12.4 GHz) and 5256A (8 GHz - 18 GHz) form the other. Figure 7 shows functional block diagrams for both classes.

Figure 7. Functional Block Diagrams of Hewlett-Packard Heterodyne Converters



These converters translate an unknown high frequency signal, F_X, to a lower frequency by mixing it with a precisely known signal of slightly different frequency. The resulting difference-frequency signal is counted by the electronic counter. Then, if the known signal is lower in frequency than the unknown, the counter frequency is added to the known frequency to find the unknown. If the known frequency is higher than the unkown, the counter reading is subtracted from the frequency. Note that these converters were designed specifically for use with the 5245L type of conventional counters. The fact that the Computing Counter can be used with the heterodyne converters to measure pulsed RF as accurately as a CW measurement is a tribute to its versatility. Operating procedures are given below.

200 MHz to 3 GHz Pulsed RF Measurements

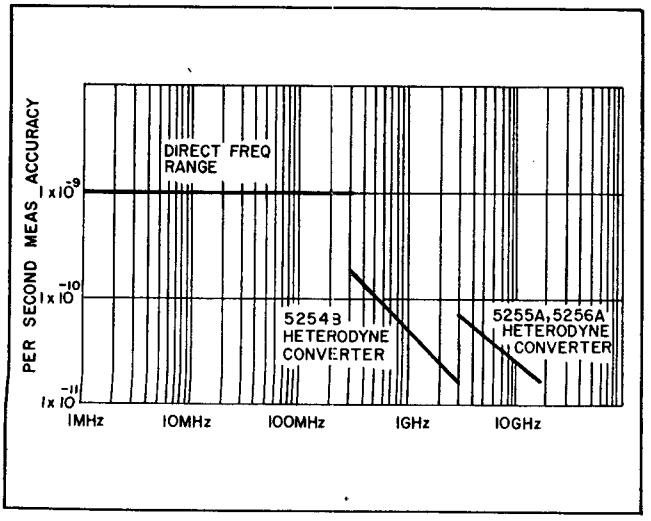
Pulsed RF measurements with the 5254B must be made by jumpering the 1-50 MHz Auxiliary Output of the 5254B to Channel B of the 5365A Input Module. This is because the 5254B Trigger Circuit (see Figure 7(a)) was designed for CW only, and the presence of large coupling capacitors prevents operation through the plug-in. Note that CW measurements made through the plug-in are perfectly satisfactory.

The procedure used to make the measurement is therefore only slightly different than that described for the direct frequency range. If the 180A Oscilloscope is used to generate the trigger, the jumper from AUX OUT to Channel B should also be connected to one input of the oscilloscope.

The high sensitivity of the Computing Counter allows input levels as low as -35 dBm to be measured; this is well below the rated sensitivity of the 5254B. Tuning the converter is best achieved with the oscilloscope display.

Pulsed RF measurement accuracy is the same as CW signal accuracy for the measurement time involved. This is shown in Figure 8.

Figure 8. Per Second Measurement Accuracy vs Input Frequency



3 GHz to 320 MHz Pulsed RF Measurements

Measurements in this range can be made in the same manner as with the 5254B. Alternatively, the measurement can be made directly through the plug-in like a CW measurement. In either case, if the 180A Oscilloscope is used to generate the trigger, the AUX OUT should be connected to one input of the oscilloscope.

The average value of a pulsed RF signal is, of course, lower than a CW signal of the same magnitude. In practice (with a pulsed RF input), the level meter of the converters does not reach the green region. A lockout circuit is included in these converters to cut off the trigger circuit if the average signal level is not large enough to put the level meter indication in the green region. To measure pulsed RF through the plug-in, the lockout must be removed from circuit. This is simply done by lifting the collector of Q8 on assembly A9. Alternatively, use specials H12-5255A and H03-5256A; they have this modification incorporated.

The high sensitivity of the Computing Counter allows measurement of signal levels as low as -18 dBm. Since the level meter is of no use with pulsed RF measurements, tuning the converter is best achieved with the oscilloscope display. The counter may also be used as an indication of signal availability.

As with the 5254B, measurement accuracy is the same as CW signal accuracy for the measurement time involved. This is shown in Figure 8.

MEASUREMENT ACCURACY

As far as the Computing Counter is concerned, the only difference between the measurement of pulsed RF and CW is that one is a triggered measurement, the other is not. Since both types of signals are measured directly, there is no degradation in accuracy in measuring a pulsed RF signal. Moreover, the Computing Counter is the most accurate frequency measuring device available. Compare this with past techniques. Pulsed RF accuracy with a transfer oscillator is degraded by the ratio of the unknown to local oscillator frequencies. It is also highly dependent on the dexterity and experience of the operator. The same applies to the wave meter which, at best, provides 3 digits of accuracy.

To ensure that the great potential accuracy of the Computing Counter is attained while measuring pulsed RF, versatile measurement controls, described earlier, are available to the user. Their usefulness is emphasized by the oscillogram of Figure 6. The width of the pulsed RF input signal, shown by the upper trace, is a little greater than 5 μsec. The START-STOP output, 5 μsec wide, is shown in the lower trace. By setting the internal measurement time at 5 μsec, the user has ensured maximum possible accuracy. Note the intensified spot on the upper waveform. This is where the oscilloscope's delayed sweep is generating the trigger for the Computing Counter.

The Computing Counter makes a frequency or period measurement with the following accuracy:

$$\text{Measurement Accuracy} = \pm \frac{1 \times 10^{-9}}{\text{Measurement Time}} \pm \text{Time Base Stability} \pm \text{Trigger Error}$$

Any error due to the time base may be removed by calibration. Trigger error is a function of the noise on the input signal and the time uncertainty this causes in the trigger circuits. For a Channel B input of 100 mV RMS with a 40 dB S/N ratio, the trigger error is given by:

$$\pm \frac{3 \times 10^{-4}}{n}$$

where n = number of periods of the input signal over which the measurement took place.

Figure 8 shows the measurement accuracy of the Computing Counter plotted for input frequencies from 1 MHz to 18 GHz. Trigger error is ignored in this plot because its effect on accuracy is dependent upon the noise on the signal. In practice, trigger error is rarely a factor for anything but the noisiest or lowest frequency signals.

TRIGGERED MEASUREMENTS

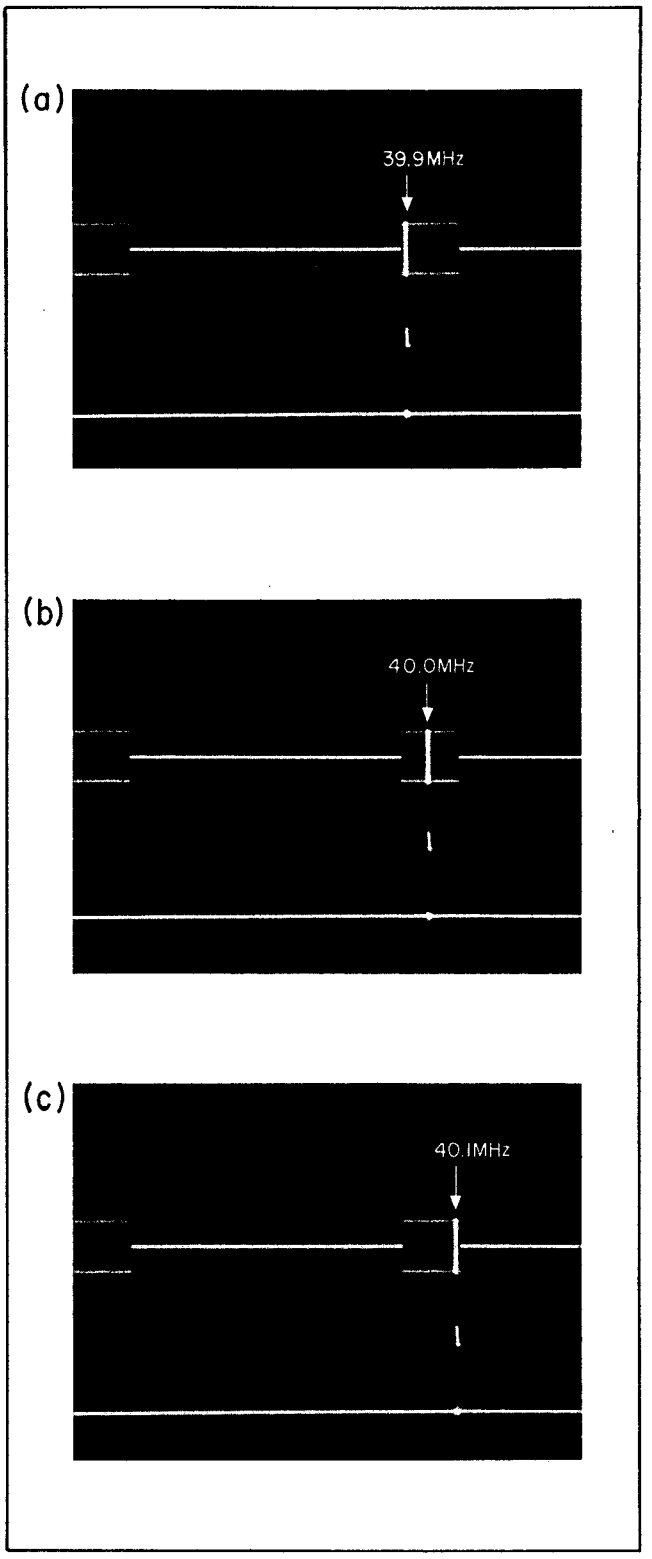
Being able to trigger the counter means a measurement can be started at any point across a pulsed RF burst. By using a small measurement time in relation to the pulse width, the frequency at any point within the RF burst can be measured. This is illustrated by the oscillograms of Figure 9. Any FM or frequency perturbations across the pulse can now be measured to counter accuracy in the same manner as they were detected in these oscillograms. The oscilloscope display and START-STOP output are invaluable for such measurements. This allows clear definition of the point at which the measurement is being made on the input signal.

PULSED RF DUTY CYCLE

Since the Computing Counter makes a direct measurement of the pulsed RF frequency, the measurement is not limited by duty cycle. Thus, the Computing Counter can measure the frequency of a single shot of pulsed RF. This applies across the whole frequency range of the counter, .01 Hz to 320 MHz with the 5365A Input Module and 320 MHz to 18 GHz with the 5254B, 5255A, and 5256A heterodyne converters. With the heterodyne converters, of course, prior knowledge of the input frequency, to within the converter's bandwidth, must be known.

Prior to the introduction of the Computing Counter, no commercially available instrument could perform such a measurement.

Figure 9. Measuring the FM Content Across the RF Burst: Upper Trace: Input Signal. Lower Trace: START-STOP Output



INCREASING THE RESOLUTION

A powerful feature of the Computing Counter is the ability to externally program the instrument's arithmetic unit. One particular program, a running

average, can be used to increase the resolution of a pulsed RF measurement. The average frequency $\overline{f}$ of N measurements is displayed where:

$$\overline{f} = \frac{1}{N} \sum_{i=1}^{N} fi$$

As each new measurement is made, the average is updated and displayed in real time. The improvement in resolution is almost two orders of magnitude over that of a single measurement. By using this program, changes in the input frequency of a pulsed RF signal, too small to detect on a direct measurement, can not only be detected but measured. Alternatively, random frequency variations in the input signal can be averaged out.

The program can be entered in one of two ways: 1) with the 10538A Program Shell, or 2) with the 5375A Keyboard. The Program Shell features simplicity of operation; simply plug it into the rear-panel EXTERNAL CONTROL connector, and press the front-panel EXT pushbutton. The instrument then runs a continuous average of the frequency being measured. To start a new average, merely press RESET. The Keyboard on the other hand is more versatile; in fact, it can perform an infinite number of arithmetic operations. This feature allows you to display solutions to equations in which frequency is the variable rather than displaying the frequency itself. Weighted averages, for example, allow detection of small, slowly varying changes in frequency. Alternatively, the short term stability or fractional frequency deviation of the signal may be measured and displayed. Keyboard programs for average, running average, and weighted average are given in the Appendix.

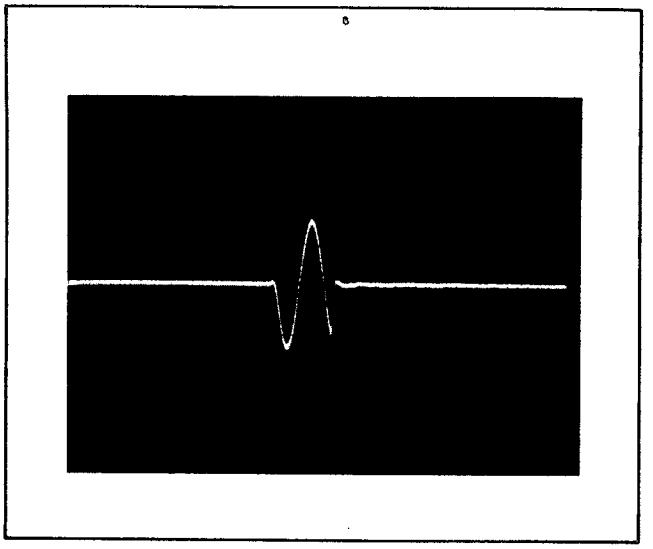
MINIMUM PULSE WIDTH

.01 Hz to 320 MHz — The Direct Frequency Range

As a period measuring instrument, the Computing Counter always makes a frequency or period measurement over an integral number of cycles of the input signal. With the front-panel MEASUREMENT TIME switch set to MIN a frequency or period measurement is made over just one cycle of the input to Channel A (. 01 Hz to 10 MHz) or 32 cycles of the input to Channel B (1 KHz - 320 MHz).

Theoretically then, the minimum measurable pulsed RF width with the 5360A/5365A is just one cycle to Channel A or 32 cycles to Channel B. In practice, it takes a little longer than this. The signal must cross the hysteresis limits of the input trigger both to start and to stop the measurement. This is illustrated by Figure 10. The pulse width of the 10 MHz pulsed RF signal is the minimum measurable by Channel A of the 5365A Input Module. As may be seen, the width is only slightly greater than the 100 nsec period of the input signal.

Figure 10. Minimum Pulse Width of 10 MHz Pulsed RF Signal



The minimum pulsed RF width is clearly a function of the carrier frequency. The relationship between the carrier frequency and the minimum pulse width is given by Figure 11.

200 MHz to 3 GHz — Using the 5254B Heterodye Converter

Even though the 5254B heterodyne converter was designed to measure the frequency of a CW signal only, its performance in measuring pulsed RF is surprisingly good. Pulsed RF signals with pulse widths only 3 μsec wide or less can be measured across the converter's entire 200 MHz to 3 GHz frequency range.

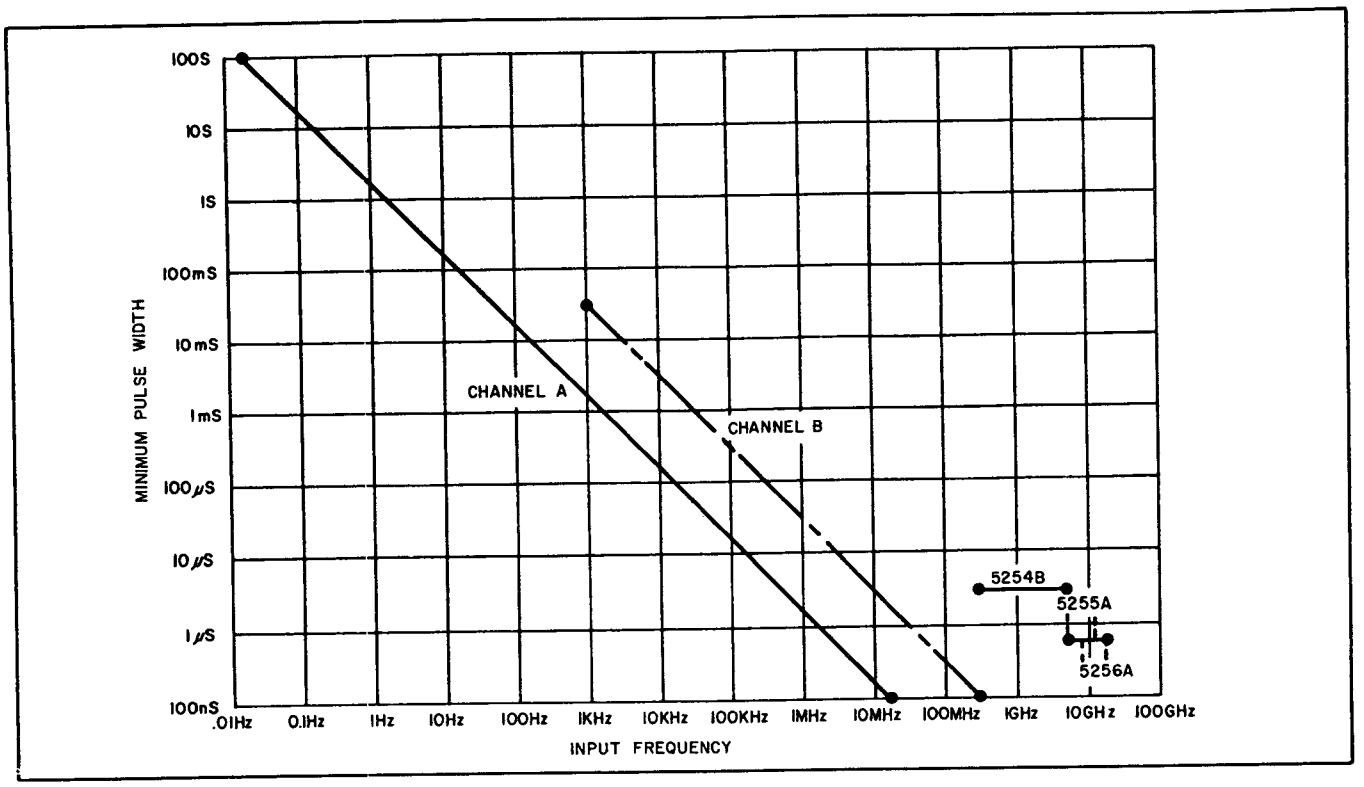
To obtain optimum performance with this converter, particularly with narrow pulse width inputs, the following should be noted:

1. Keep the RF input level below -25 dBm. Because of the single ended mixer, a transient occurs at the leading edge of the pulse burst - the higher the input level, the longer the elapsed time before this transient disappears and a measurement can begin. The high sensitivity of 5365A input B allows measurement of RF inputs with levels below -35 dBm with no degradation in accuracy.

2. Keep the IF output frequency to 25 MHz or greater. Since the IF output is the frequency actually being measured by the Computing Counter, shorter measurement times are obtained with higher IF frequencies (assuming the 5360A MEASUREMENT TIME switch is at MIN).

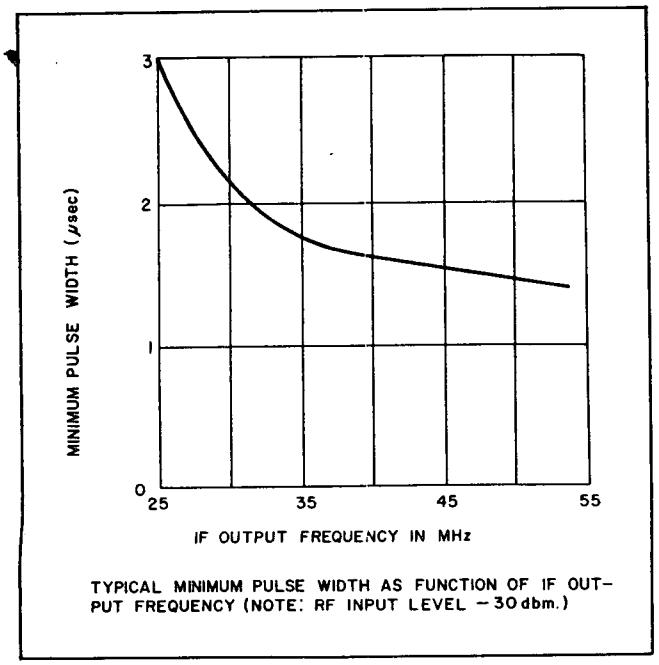
The minimum pulse width as a function of IF output frequency is shown in Figure 12.

Figure 11. Minimum Pulse Width as a Function of RF Carrier Frequency



Notice that no matter what the input frequency, an IF of 25 MHz or greater can be obtained. In cases where the input is less than 25 MHz above the nearest converter harmonic, tune to the next highest harmonic and subtract rather than add the measured IF.

Figure 12. Pulsed RF with 5360A and 5254B Heterodyne Converters



TYPICAL MINIMUM PULSE WIDTH AS FUNCTION OF IF OUTPUT FREQUENCY (NOTE: RF INPUT LEVEL −30 dbm.)

3 GHz to 18 GHz — Using the 5255A, 5256A Heterodyne Converters

The situation here is similar to that of the 5254B, but now even shorter pulsed RF bursts can be measured. Pulsed RF signals with pulse widths of only 700 nsecs, or even less, are measurable across the entire frequency range covered by both converters.

To enable measurements of such short-width pulse bursts, a minor modification is required to both converters. This consists of changing C2 and C3 on the video amplifier assembly A7A1 to 100 pF each*. While this increases the lower frequency cut-off of the IF output from less than 1 MHz to approximately 7 MHz, any frequency within either converter's range is still measurable. The considerable overlap at the upper end of the frequency response of both converter's IF outputs ensures this.

All measurements involving very short pulse widths have to be made by jumpering the IF output to Channel B of the 5365A Input Module. Making the measurement through the module avoids the divide-by-four prescaler in the converters which would increase the minimum measurement time by a factor of four.

*Specials H12-5255A and H03-5256A have these modifications incorporated.

As with the 5254B, best results are obtained with a low level input signal. The high sensitivity B input of the 5365A Input Module allows measurement of signal levels as low as -15 dBm. The optimum level is approximately -10 dBm, although this is best found by trail and error.

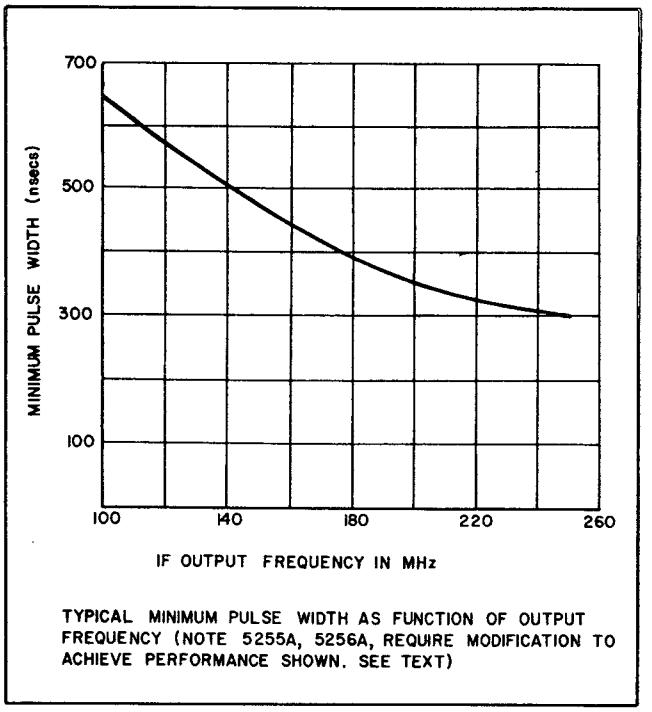
The IF output frequency should be kept at 100 MHz or greater. No matter what the input frequency, an IF of 100 MHz or greater can be obtained. In cases where the input is less than 100 MHz above the nearest converter harmonic, tune to the next highest harmonic and subtract rather than add the measured IF. This procedure ensures the minimum measurement time for all input frequencies. The typical minimum pulse width as a function of IF frequency is shown by Figure 13.

MEASUREMENT OF PULSED RF WITH NO TRIGGER

If the pulse repetition frequency is less than 300 Hz*, a trigger is not necessary. In this non-triggered mode of operation (TRIG-NORM switch in NORM) the measurement always starts at the leading edge of the pulsed RF burst. To ensure that the pulsed RF is synchronized with the sampling rate of the counter, the CYCLE RATE should be set to MAX. Also the MEASUREMENT TIME should be set to cover as much of the pulse burst as possible.

*Above 300 Hz, answers can still be obtained, but occassionally erratic readings will be observed.

Figure 13. Pulsed RF with 5360A, 5255A, and 5256A Heterodyne Converters



TYPICAL MINIMUM PULSE WIDTH AS FUNCTION OF OUTPUT FREQUENCY (NOTE 5255A, 5256A, REQUIRE MODIFICATION TO ACHIEVE PERFORMANCE SHOWN. SEE TEXT)

APPENDIX

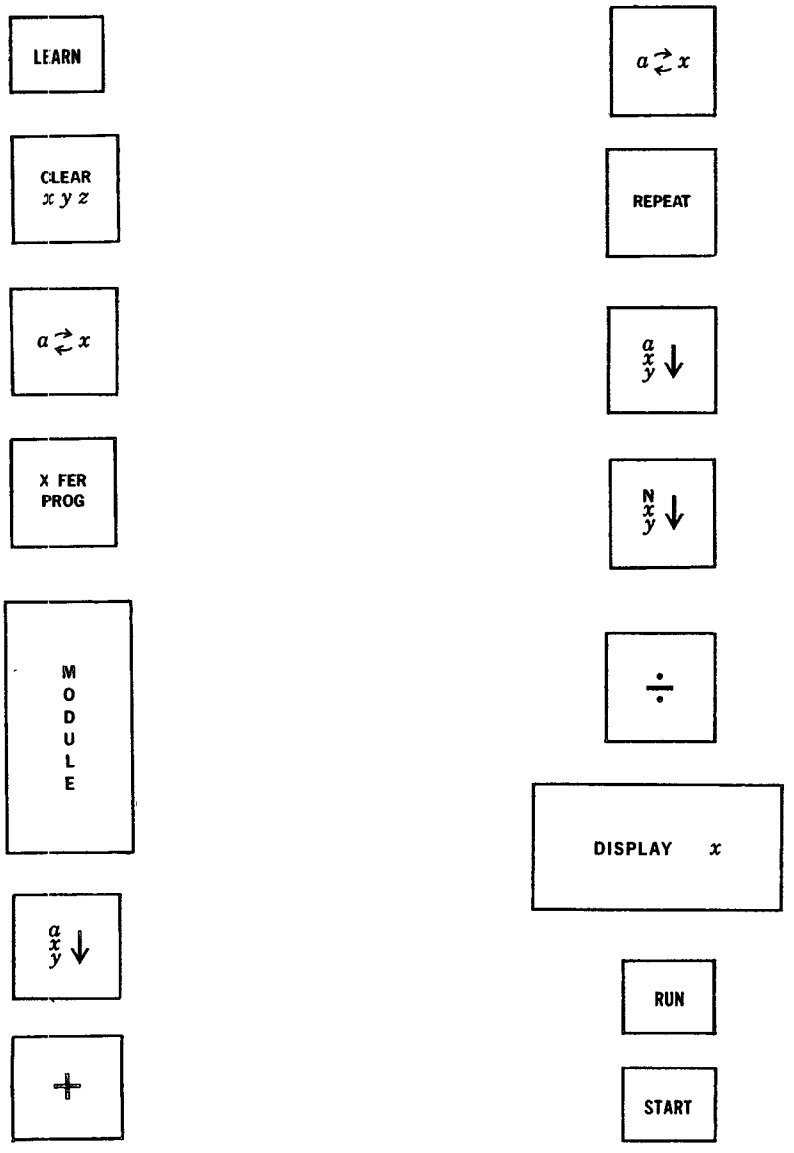
The Appendix provides useful programs for the 5375A Keyboard/ 5360A Computing Counter combination. Programs are included for average, running average, and weighted average.

Program for Average of N Measurements

Calculates the average of a preset number of measurements.

Initially: Set REPEAT LOOP (N=) switch to desired number of measurements to be averaged.

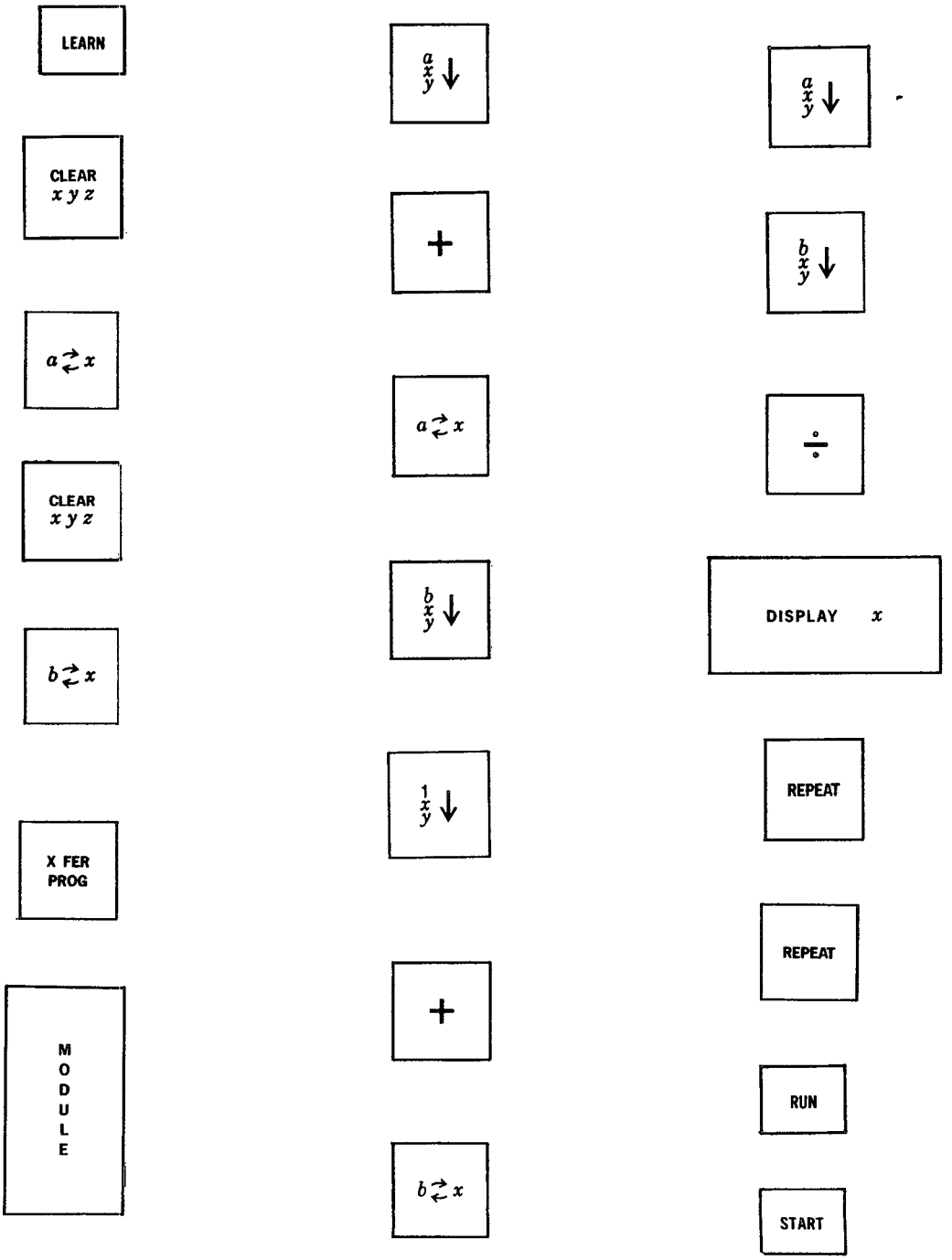
Proceed as follows:



Calculates a continuous average of all measurements taken through the Input Module.

Initially: Set REPEAT LOOP (N=) to any setting except 1.

Proceed as follows:



Program for Weighted Average

Calculates $M_N = \frac{(x - 1)\, M_{N-1} + f_N}{x}$

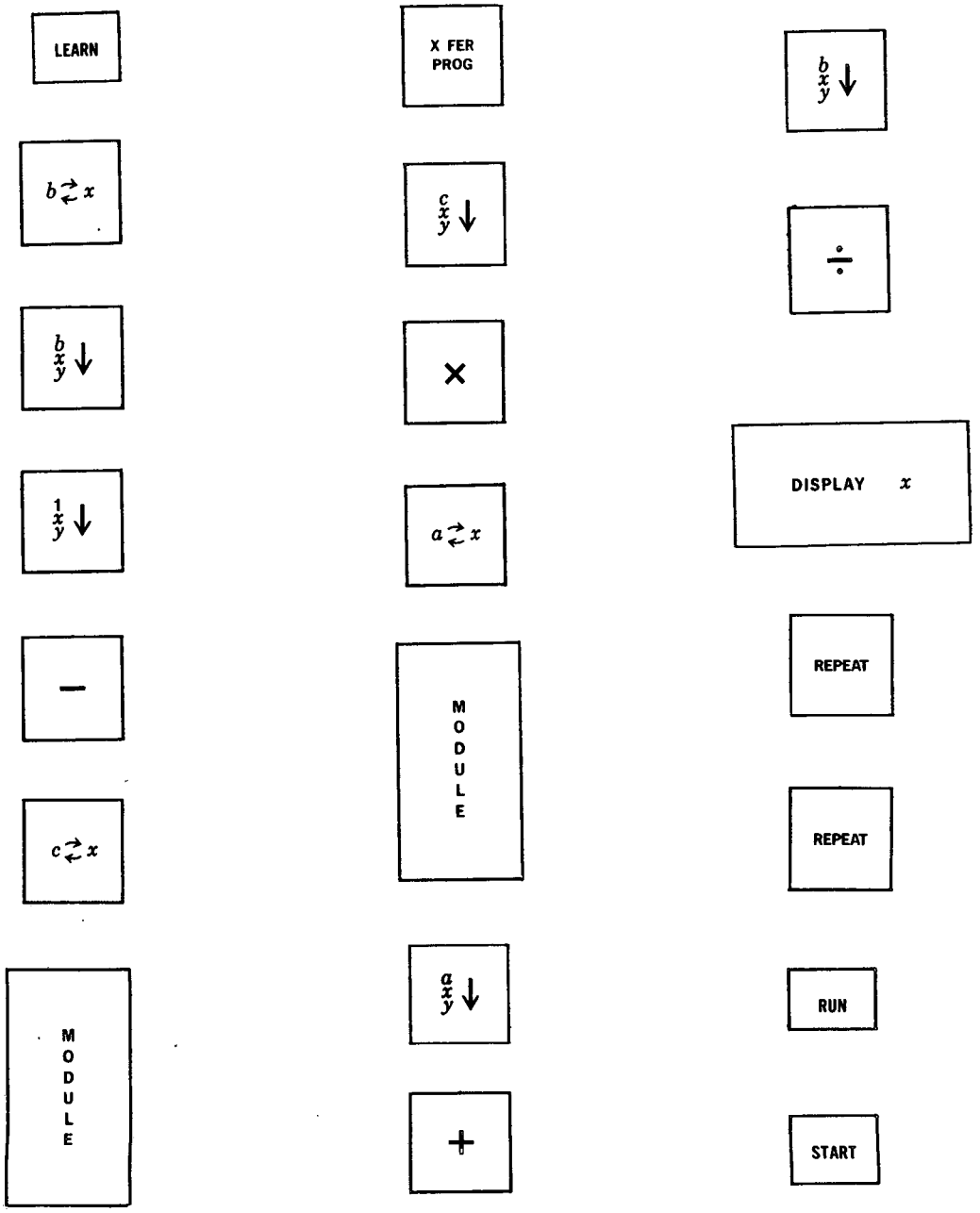
Where M_N = Nth "average"

f_N = Nth measurement

x = Weighting function consisting of any positive integer.

Initially: Set REPEAT LOOP (N=) to any setting except 1, load x (in formula) into x register.

Proceed as follows:



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