



A 0-50 Mc Frequency Synthesizer with Excellent Stability, Fast Switching, and Fine Resolution

DIGITAL FREQUENCY SYNTHESIS

About twelve years ago the digital frequency counter made its commercial debut. It revolutionized the art of frequency measurement; and a tedious, complex process of multiple heterodyning was reduced to a simple act of plugging in the signal and reading the answer. The tremendous time saving more than justified the cost of the counter and these instruments have become ubiquitous. They are found today in applications undreamed of a decade ago.

With the advent of the digital frequency synthesizer I believe we face an analogous situation. Here we have a single instrument that can generate any frequency over a range far greater than most oscillators or signal generators — a frequency known to quartz crystal accuracy of a part in 10^{10} or better. This one instrument can do the work of a whole battery of general- and special-purpose generators and do it better and more conveniently. The initial model has been engineered to the most exacting specifications and construction to meet the need for a high-performance instrument. Later lower-priced models will provide high performance over a reduced frequency range.

It will be very interesting to watch the applications develop for frequency synthesizers. Almost certainly they will become as common as counters. Almost certainly there are applications in your own work where a synthesizer would save time and money and do a better job.

Bernard M. Oliver
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Fig. 1. New *hp* Model 5100A/5110A Frequency Synthesizer generates high-stability signals in 0.01 cps increments from dc to 50 megacycles. Generated frequency can be controlled by panel keyboard or by remote control. Programmed control tapes can be used to specify frequency patterns for automatic testing, fast receiver tuning, NMR work, etc.

AS THE ELECTRONIC art has advanced, so has the need for variable-frequency signal sources of high stabilities — stabilities comparable to those obtained from high-quality frequency standards. Such sources are valuable in sophisticated communications work, radio sounding, radar, doppler systems, automatic and manual testing of frequency-sensitive devices, numerous timing situations, spectrum analysis, stability studies, and many other areas.

The sources that provide highest frequency-stability are single-frequency sources — “frequency standards.” Today, some of these are refined to the extent that they use atomic resonance for maximum long-term stability with a highly-developed quartz oscillator as a “flywheel” for maximum short-term stability. Having these high-quality standards in hand, it is natural to look for some method to translate their stability to other desired frequencies. This translation, when the operation is something more than a

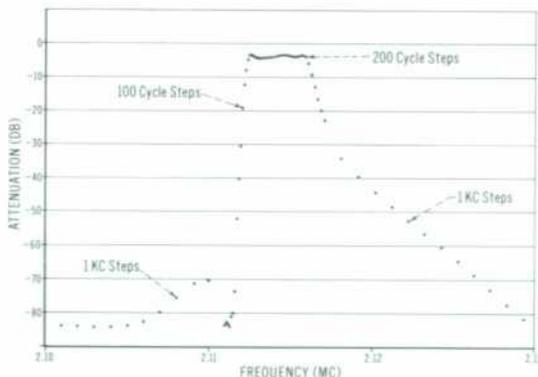


Fig. 2. Amplitude response of crystal filter made using synthesizer in setup of Fig. 4, which permits automatic plotting if desired. Phase plots of many devices can be similarly made to check device stability.



Fig. 3. -hp- Model 5100A Synthesizer (upper unit) with Model 5110A Synthesizer Driver (lower unit). One Driver unit can operate up to four Synthesizer units.

single arithmetic operation, is commonly known as frequency synthesis. Hence, a variable-frequency synthesizer is an instrument that translates the frequency stability of a single frequency, usually one from a frequency standard, to any one of many other possible frequencies, usually over a broad spectrum. Such an instrument may provide any one of thousands, even billions, of frequencies. In everyday usage the word "variable" is usually omitted from the name, and the instruments are called merely "frequency synthesizers."

The two basic approaches to frequency synthesis are known as "direct" (or "true") and "indirect." Direct synthesis simply performs a series of arithmetic operations on the signal from the frequency standard to achieve the desired output frequency. The indirect method involves the use of tunable oscillators which are phase-locked to harmonics of signals derived from the standard.

The direct-synthesis approach has the pronounced advantages of permitting fine resolution and fast switching in the same instrument, as well as fail-safe operation and an extremely clean output signal. For these reasons it has been selected as the design approach for a sophisticated new synthesizer developed by the -hp- Frequency and Time Laboratories.

The new synthesizer, for example, provides frequencies from 0.01 cps to 50 megacycles in digital increments as fine as 0.01 cps! — a total of 5 billion discrete frequencies. At any frequency the out-

put is a spectrally-pure signal — any non-harmonic spurious signal is more than 90 db below the desired signal.

The output frequency can be selected by front-panel pushbuttons or by remote electronic control for work involving automatic testing or fast frequency tracking. Under electronic control, the transition from one frequency to any other can be accomplished in much less than 1 millisecond, as described later.

The stability of the frequencies is derived from a self-contained frequency standard which has excellent short-term stability and a maximum drift rate of 3 parts in 10^9 per day. The high-frequency short-term stability, which includes noise as well as spurious signals, is quite comparable to that of a quality frequency standard. An external standard can also be used if desired.

PHYSICAL ARRANGEMENT

The Synthesizer is divided into two units, (Fig. 3), both of which are completely solid-state. The upper unit is the Synthesizer proper and the lower the Driver. Manual selection of the output frequency is made by the keyboard frequency control on the Synthesizer; remote electronic control is permitted by a switch at the lower left of the unit.

The pushbutton keyboard allows single-button frequency steps as great as 10 megacycles in the left column and as fine as 0.01 cps in the right. An extra row of "S" (Search) buttons across the top of the keyboard permits continuous variation of the output frequency either manually or remotely by external voltages. This gives continuous frequency cover-

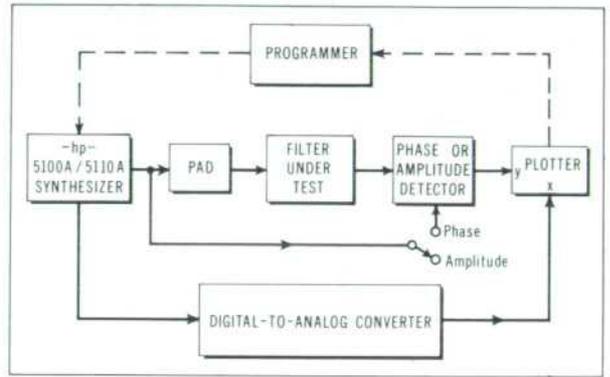


Fig. 4. Equipment setup for making response record of Fig. 2. Phase plots can be made using phase detector. System can make measurements automatically using suitable programmer.

age and facilitates frequency-search work. Manual searching is provided for in the form of a panel control which is calibrated from 0 to 10, corresponding to the full-scale frequency rating of the column being searched.

SYSTEM OPERATION

A simplified block diagram of the overall instrument is shown in Fig. 5. The Driver (Model 5110A) contains a frequency standard, a spectrum generator, and appropriate selection networks to provide a series of fixed frequencies between 3 and 39 Mc to the Synthesizer unit. The Synthesizer unit (Model 5100A) contains harmonic generators and suitable mixers, dividers, and amplifiers to derive the desired output frequency as a function of the fixed frequencies.

The fine resolution portion of the instrument is particularly interesting and also serves to illustrate the method of synthesis used. As shown in the right-hand portion of Fig. 5, there are seven identical mixer-divider units, each of which corresponds to a place or position in the final output frequency number. In each of these units, and in the eighth unit as well, a frequency of 24 Mc is used as a carrier input, as shown.

In the right-hand unit, which produces what ultimately becomes the highest resolution digit (10^{-2} cps), the 24 Mc carrier is added to a 3.0 Mc frequency in frequency-adder "A" to produce 27.0 Mc. In "B" the 27.0 Mc frequency is added to a frequency of from 3.0 to 3.9 Mc, depending on the setting of the panel pushbutton or remote control-circuit. Selection of a "2" in this particular digit position, for example, electronically selects a signal of 3.2 Mc from the Driver.

The output of "B" is a frequency of 30.0 to 30.9 Mc, which is divided in "C"

to produce 3.00 to 3.09 Mc. This frequency is applied to the second unit, where it adds with the 24 Mc carrier as before and the process repeats. If the process is followed through, it will be seen that the frequencies noted in the block diagram are obtained at the outputs of the various adders and dividers. In essence, each mixer-divider unit, through a frequency division process, moves a given digit one place to the right in the final frequency and at the same time inserts a new number in the displaced position. The final result is that the output of the eighth unit is a frequency of between 30,000,000.00 and 30,999,999.99 cps, depending on the output frequency selected¹.

In the following two operations the signal is added to a frequency of 330 Mc, and the resultant again added to an appropriate frequency between 30 and 39 Mc to yield a frequency of between 390 and 400 Mc. One of the five frequencies from 350 to 390 Mc is then subtracted from this to yield the desired 0.01 cps to 50 Mc output frequency.

SEARCH OSCILLATOR

The search feature has proved useful in several ways. Besides facilitating searching for an unknown frequency, it permits smooth frequency modulation of the output, phase-locking the synthesizer into another system, sweep operation with a sweep width smaller than 0.1 cps, and the capability of placing the sweep accurately anywhere within the instrument range. The search oscillator permits the output frequency to be continuously varied over the frequency range of any one column except the left-hand two (megacycles and tens of megacycles columns). Searching can be done either manually by a panel control or electronically by an external voltage of -1 to -11 volts.

In the circuit, the search oscillator is a 3.0 to 4.0 Mc variable oscillator that is substituted for the 3.0 to 3.9 Mc fixed frequencies available to the filter-divider units (1-8 in Fig. 5). Its manual control is calibrated to 3% accuracy and its voltage control capability has a 5% linearity specification. The RMS Δf contributions of about 1 cycle for second averaging when this oscillator is searching in the 100 kc step position

¹ Synthesis methods similar to this have been considered by several people including some at Hewlett-Packard. Especially significant work in this area was carried on for many years by H. Hastings and R. Stone at the U. S. Naval Research Laboratory.

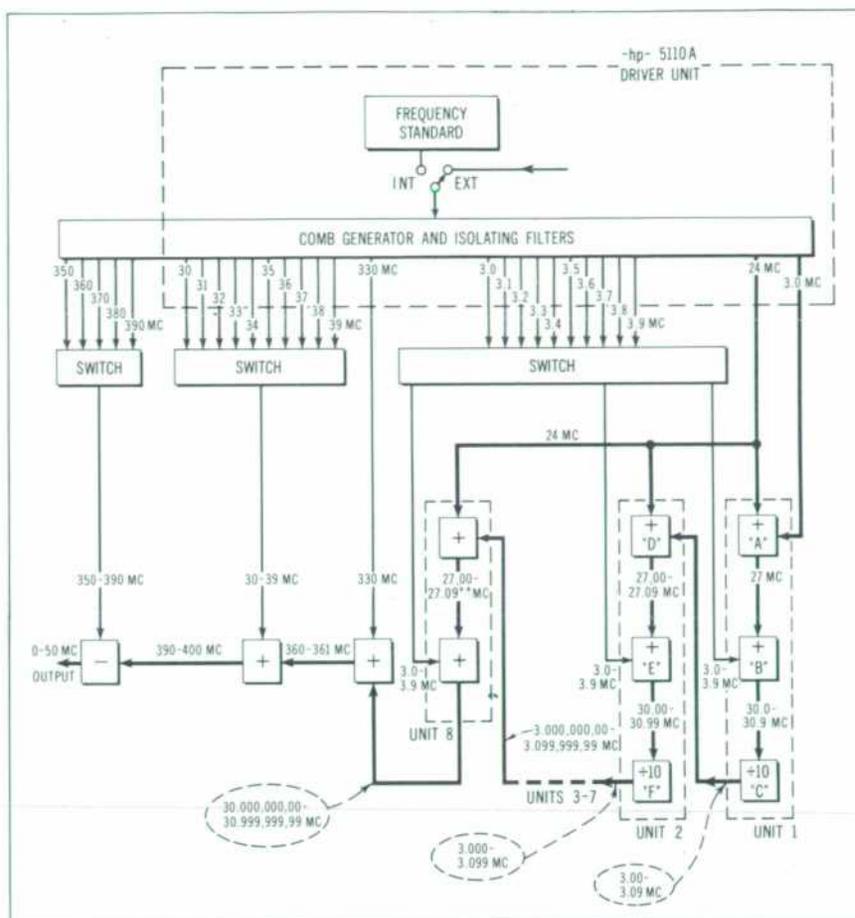


Fig. 5. Basic circuit arrangement of Model 5100A/5110A Frequency Synthesizer. Direct-type synthesis design approach is used to achieve fast switching with fine resolution and fail-safe type circuit.

limits the synthesizer's short-term stability to that extent, but in search work this is presumably of little consequence. At any rate, the instability effects are reduced as the digital position of insertion is made less significant because of the frequency dividers involved. Insertion in the 10-cycle step position does not result in a significant reduction of the synthesizer's short-term stability.

SIGNAL PURITY

One of the important design objectives for this system was the elimination of non-harmonically-related spurious signals to a -90 db specification. A parallel design objective was the reduction of noise to as low a level as possible, since noise appears as a small random phase modulation which, in critical high-stability work, adversely affects the frequency stability of the signal. Some sources of noise are standard oscillator instabilities, filter instabilities, thermal and current noise introduction at low level points, 1/f reactance noise in tuned circuits, electrical contact problems, and semiconductor breakdown.

Fig. 6 shows the low value of the phase noise distribution typical of the new synthesizer (the AM noise is some 20 db further down within 100 kc). The synthesizer's contribution to a "perfect" external standard would be somewhat less than indicated for the noise closer than 100 cycles. This close-in noise is



1 AND 10 MC SYNTHESIZERS

Two additional synthesizers, based on the same design approach used in the 50-Mc synthesizer described in this issue, will soon be placed in production. The chief difference in these units is that their upper frequency limits are 1 and 10 Mc, respectively. Their general performance, while not precisely the same as the first, has been kept at a high level. Frequency selection is also made either by panel pushbuttons or by remote control.

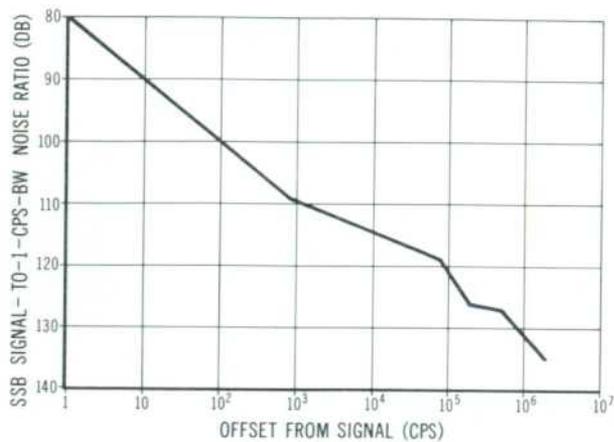


Fig. 6 (a)

also less for lower output frequencies. Multiplication to X-band and analysis with 1-cycle-bandwidth analyzer shows the spectral width to be much less than 1 cycle (Fig. 7).

In an attempt to give a rough indication of the synthesizer's noise performance, we have specified that the phase noise in an arbitrarily-selected 30 kc noise bandwidth (excluding 1 cycle at the center) centered on the signal will be more than 54 db down (see specifications). The contribution within 100 cycles is less at lower frequencies, so the specification is most conservative there. In a like bandwidth the AM noise will be more than 74 db down for output frequencies above 100 kc.

In order to characterize the synthesizer's performance for timing applications, we have specified the RMS fractional frequency deviations in terms of this same 30-kc bandwidth. One advantage of this characterization is that the same number holds after processing the signal through a perfect frequency multiplier or divider. The specifications given are most conservative at the lower output frequencies for the longer averaging times. The specifications can be viewed as applying to the synthesizer including the internal standard or as RMS contributions to a very high quality external standard. For averaging times of a second or longer, the synthesizer can convert the stability of the best single-frequency standards to the 50 Mc region without significant deterioration.

LEVEL STABILITY

The level stability of the equipment is of considerable importance in some applications such as in frequency multiplication where level instability can be converted to phase instability. The specifications include both the effects of

frequency change and environmental conditions. Fig. 8 shows a sample instrument output level as a function of frequency. Improved response from dc to 100 kc is provided by a low-level, high-impedance output. Level stabilities as a function of time and of line voltage are shown in Fig. 9.

SWITCHING SPEED

The provision for fast electronic frequency selection makes the Synthesizer's resolution and stability available for such tasks as automatic digital frequency tracking, automatic testing of frequency-sensitive devices, automatic special communications systems, as well as simple remote control or readout of frequency.

When the LOCAL-REMOTE switch is thrown to REMOTE, the switching power is transferred from the front panel control to three remote-control connectors on the back panel of the synthesizer. Frequency control is then accomplished by connecting the switching-power line to the lines corresponding to the desired digits. With electronic control, extremely fast frequency selection can be accomplished and with virtually no dead time, as shown in the accompanying group of oscillograms.

INTERNAL STANDARD

The quality of the internal 1 Mc standard is indicated by its aging rate of less than 3 parts in 10^9 per day, which is only about one order of magnitude below that of the finest crystal standards. A standby feature keeps the internal crystal oven turned on as long as ac line-power is available. The standard is well protected from line voltage variations, the worst effect being a momentary frequency shift on the order of a few parts

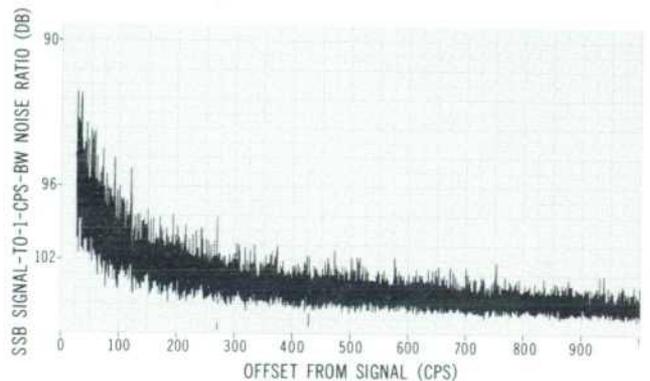


Fig. 6 (b)

Fig. 6. Typical low value of phase noise in output of new synthesizer. (b) shows "close-in" noise in greater detail. AM noise is much below these levels. Both records are of single side-band made with tunable selective system.

in 10^{11} with a fast change from low to high line ($\pm 20\%$). There is less than 2 parts in 10^{10} frequency shift per $^{\circ}\text{C}$ change in the ambient temperature.

The internal standard can be adjusted by an external voltage to permit locking the synthesizer into some other system. A range of ± 5 parts in 10^8 frequency control can be exercised with a ± 5 -volt external source. The short-term stability of the standard is adequate to provide the short-term stability specified for the overall instrument.

When an external standard is used in place of the internal standard, a crystal filter and other circuits in the synthesizer improve to a greater or lesser extent the noise and spurious signal modulation present on that standard. A measure of this improvement is indicated in

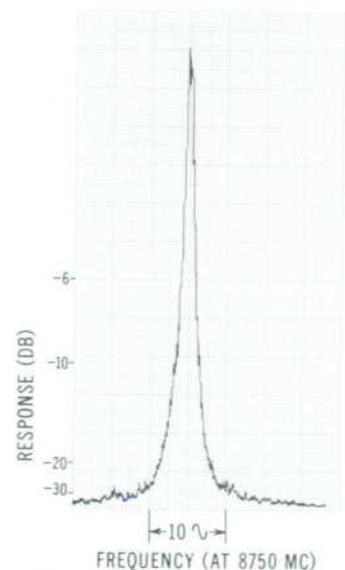
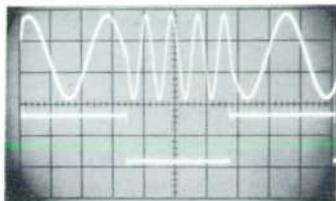
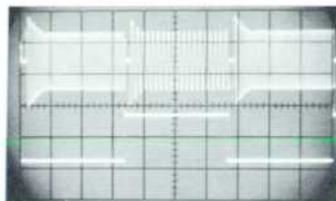


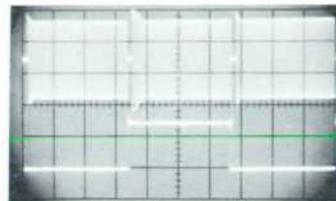
Fig. 7. Spectrum of typical synthesizer signal when multiplied to X-band. Narrow width here of < 1 cps indicates high quality of original synthesizer signal.



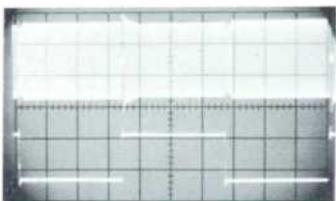
(a) (Upper trace) Synthesizer frequency switched from 20.003 Mc to 20.006 Mc and back with 20 Mc subtracted to display switching in greater detail. This switching detail is typical of any of the six right-hand places. Sweep speed is 200 μ sec/cm.



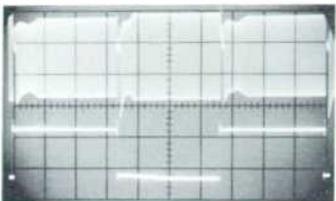
(b) Synthesizer switched between 20.03 Mc and 20.06 Mc with 20 Mc subtracted. Sweep is 200 μ sec/cm. Lower trace in all cases is switching waveform applied to synthesizer.



(c) Synthesizer switched between 20.3 Mc and 20.6 Mc. No subtraction. Sweep is 200 μ sec/cm.



(d) Synthesizer switched between 23 Mc and 26 Mc. Sweep is 100 μ sec/cm.



(e) Synthesizer switched between 10 Mc and 20 Mc. Sweep is 100 μ sec/cm.



(f) Synthesizer switched between 19.99 Mc and 20 Mc. Sweep is 200 μ sec/cm.

SYNTHESIZER SWITCHING SPEED

The accompanying oscillograms show the tremendous speed with which the synthesizer can change its output frequency under electronic control. The upper waveform in each case is the synthesizer output as it is changed from one frequency to another and back again. The lower waveform is the external switching voltage applied to the synthesizer. The oscil-

lograms have been selected to show switching both within a single place (digit column) and between various places of the output frequency.

In all cases a fast sweep speed of 200 microseconds/cm or faster has been used in order to adequately portray the speed of switching and the virtual non-existence of switching transients. Any frequency instabilities at the start of the new frequencies are

not revealed by such oscillograms, but these have been determined by other means to be very slight and brief in duration.

The switching waveform was derived by applying an external positive voltage of +2 volts in series with a contact closure as the "off" signal. A simple contact opening without an external voltage can also be used as the turn-off signal at a moderate reduction in switching speed and turn-on clarity.

Fig. 10 which shows the conversion of modulation on the driving standard to modulation on the synthesizer output at both a high and a low frequency.

For some applications it is desirable to bypass the crystal filter in the synthesizer so that the external standard may be shifted or frequency-modulated. Therefore a pair of curves is also shown in Fig. 10 for operation without the filter.

The improvement resulting when using the filter may cause a measurement ambiguity if the synthesizer output is checked for short-term stability against an external driving standard. Such a comparison would usually be expected to show the synthesizer contribution, but in this case, where the signal from the synthesizer may be an improved version of that from the driving standard, the measurement may really be a measurement of the noise on the standard. In other words, *evaluating the synthesizer contributions requires an extremely high-quality standard.*

ENVIRONMENTAL PERFORMANCE

The synthesizer is specified to operate over an ambient temperature range that is quite wide — 0 to 55°C. Consequently, the effects due to ambient temperature changes of usual amounts are small. For example, exclusive of the frequency standard, the phase shift per °C is typically $6^\circ + .25^\circ/\text{Mc}$. Converting this to fractional frequency error, we have

$$\frac{\Delta f}{f} = N \left(\frac{5}{F} + 0.2 \right) \times 10^{-12},$$

where N is the rate of temperature change in degrees per hour and F is the output frequency in megacycles. At 50 megacycles with a 1°C/hour rate of ambient temperature change, this would amount to but 3×10^{-13} frequency error.

The internal frequency standard has a typical frequency shift of ± 1 part in 10^{10} per °C (normal for a high quality standard), so that the *frequency stability* of the system above 100 kc will normally be limited by the frequency standard. The best available quartz standards

have a temperature dependence of about 20×10^{-13} per °C. The Synthe-

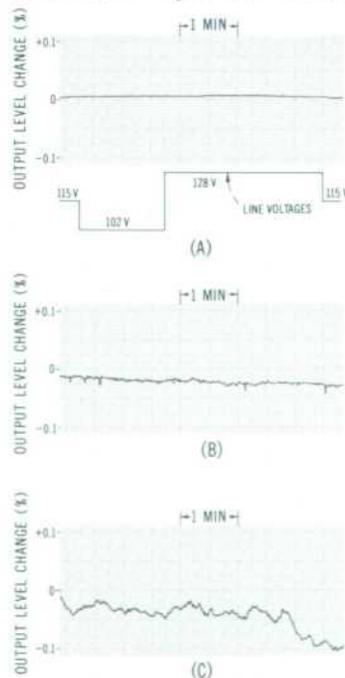
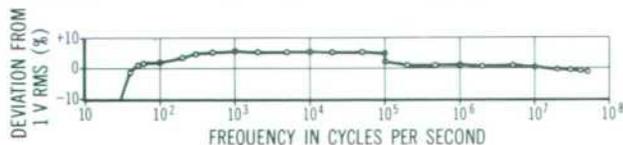


Fig. 9. Recordings showing high output voltage stability of new synthesizer. (a) is typical of outputs above 100 kc, (b) below 100 kc. Line voltage in (a) and (b) was varied widely as shown in (a). For comparison, (c) shows stability of a quality LC oscillator operating on a constant-voltage regulated line.

Fig. 8. Typical synthesizer output level vs. frequency.



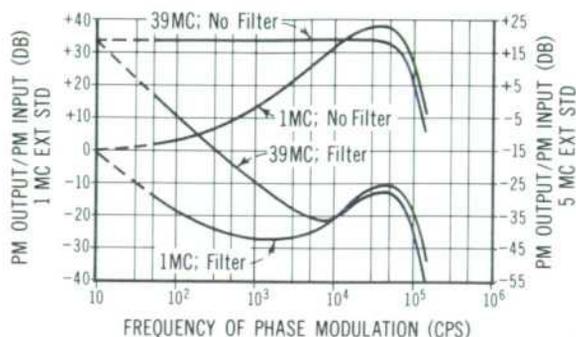


Fig. 10. Noise "cleanup" produced by synthesizer on a frequency synthesized from external signal compared with the external signal. Curves are given both for case where synthesizer's internal filter is used and when not used.

sizer and Driver performance are presently being checked at 55°C before shipment as a quality assurance measure. No damage will result from non-operating exposure to -40° to +75°C.

Tests on sample instruments show that these instruments can be expected to meet the specifications under a combination of both 95% relative humidity and 40°C temperature even after a few 24-hour cycles of low to high humidity.

The specifications on short-term stability are given for a vibration-free environment. The typical slight degradation of short-term stability for the system exclusive of the frequency standard is indicated in Fig. 11. No damage was experienced on a sample instrument-pair tested from 10 to 55 cycles with .010-inch peak-to-peak excursions in the three principle directions.

The radiated and conducted interference caused by the system falls within the limits allowed by MIL-I-16910A, and the equipment has been designed and sample-tested to meet the susceptibility conditions of MIL-I-6181D and

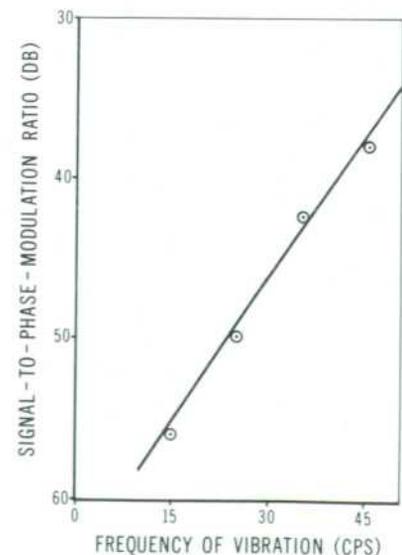


Fig. 11. Synthesizer exhibits only slight vibration effects. Curve shown is for .010" p-p excursion. Synthesizer operates under temperature and humidity extremes.

MIL-I-26600. This means that there should not be any RF interference problems when operating the synthesizer near other reasonably well-designed equipment.

Another important consideration is the spurious signal production due to external sources of low frequency (power line) magnetic fields. The synthesizer system has been carefully designed so that a field of at least 0.3 gauss is required to cause a -90 db spurious modulation of the output signal. Some electronic instruments produce considerably more than this, however. Spurious signals at the frequency of the magnetic field (and its second harmonic) will be considerably worse.

SOLID-STATE MODULES

Plated-through printed circuit board construction is used throughout. Modular construction has been used which should be a great help in any maintenance, since it is relatively easy to trace a trouble to an offending module. Modules are interchangeable with others of like kind.

ACKNOWLEDGMENT

This instrument development has been one of the largest yet undertaken by Hewlett-Packard. To bring it to production status has required more than 40 engineering man-years of development with a highly concentrated effort extending over a period of almost three years. The bulk of the electrical design work was done by David E. Baker, John N. Dukes, John E. Hasen, Albert P. Malvino, Walter R. Rasmussen (a five-year sustained effort), Hans H. Junker, Alexander Tykulsky, and the undersigned. The mechanical and production aspects were ably handled by Lawrence A. Lim, William Powell, and Theodore G. Pichel. There are, of course, many others who made valuable contributions and their efforts are greatly appreciated.

-Victor E. Van Duzer

SPECIFICATIONS

— hp —
MODEL 5100A
FREQUENCY SYNTHESIZER

OUTPUT FREQUENCY: DC to 50 Mc.

DIGITAL FREQUENCY SELECTION: 0.01 cps through 10 Mc per step. Selection by front panel pushbutton or by remote switch closure. Any change in frequency may be accomplished in less than 1 millisecond.

OUTPUT VOLTAGE: 1 volt rms ± 1 db from 100 kc to 50 Mc. 1 volt rms ± 2 db, -4 db from 50 cps to 100 kc, into a 50-ohm resistive load. Nominal source impedance is 50 ohms. 15 millivolts rms minimum open circuit from 100 kc down to DC at separate rear output connector; source impedance of 10K ohm with shunt capacitance approximately 70 pf.

SIGNAL-TO-PHASE NOISE RATIO: Greater than 54 db in a 30 kc band centered on the signal (excluding a 1-cps band centered on the signal).*

SIGNAL-TO-AM-NOISE RATIO: (Above 100 kc): Greater than 74 db in a 30-kc band.*

RMS Fractional Frequency Deviation (With a 30-kc noise bandwidth):*

AVERAGING TIME	OUTPUT FREQUENCY			
	1 Mc	5 Mc	10 Mc	50 Mc
10 milliseconds	3x10 ⁻⁹	6x10 ⁻⁹	3x10 ⁻⁹	6x10 ⁻¹⁰
1 second	3x10 ⁻¹⁰	6x10 ⁻¹¹	3x10 ⁻¹¹	1x10 ⁻¹¹

SPURIOUS SIGNALS: Non-harmonically related signals are at least 90 db below the selected frequency.

HARMONIC SIGNALS: 30 db below the selected frequency (when terminated in 50 ohms).

SEARCH OSCILLATOR: Provides continuously variable frequency selection with an incremental range of 0.1 cps through 1 Mc. Manual or external voltage (-1 to -11 volts) control with linearity of $\pm 5\%$.

WEIGHT: Net 75 lbs (34 kg); shipping 127 lbs (58 kg).

EQUIPMENT FURNISHED: 05100-6180 Decade Test cable, 05100-6066 Output cable, 05100-6157/8 cable assembly connects 5100A Synthesizer to 5110A Driver. Permits rack mounting of up to two 5100A's immediately above and/or below the 5110A Driver. Special-length cable assembly available for other mounting arrangements.

*Performance data stated are based on internal frequency standard or highest quality external standard.

— hp —
MODEL 5110A
SYNTHESIZER DRIVER

INTERNAL FREQUENCY STANDARD: 1 Mc Quartz Oscillator.

AGING RATE: $< \pm 3$ parts in 10⁶ per day.

STABILITY: As a function of ambient temperature: $\pm 2 \times 10^{-10}$ per °C from 0°C to +55°C.

As a function of line voltage: $\pm 5 \times 10^{-11}$ for a $\pm 10\%$ change in line voltage (rated at 115 or 230 volts rms line voltage).

Short term: Adequate to provide the 5100A performance noted above (1×10^{-11} rms for 1 second averaging on direct output for 30 kc noise bandwidth).

PHASE LOCKING CAPABILITY: A voltage control feature allows 5 parts in 10⁶ frequency control for locking to an external source. -5 to +5 volts required from phase detector (not supplied).

EXTERNAL FREQUENCY STANDARD:

INPUT REQUIREMENTS: 1 or 5 Mc. 0.2 v rms minimum, 5 v maximum across 500 ohms. Stability and spectral purity of 5100A Frequency Synthesizer will be partially determined by the characteristics of the external standard if used.

WEIGHT: Net 54 lbs (25 kg); shipping 60 lbs (27 kg).

GENERAL

OPERATING TEMP. RANGE: 0 to +55°C.

INTERFERENCE: Complies with MIL-I-16910A.

POWER: 115 or 230 volts $\pm 10\%$, 50 to 400 cycles, 35 watts each unit (independent supplies).

PRICE: Model 5100A Frequency Synthesizer, \$10,250. Model 5110A Synthesizer Driver, \$5000.

Prices f.o.b. factory.

Data subject to change without notice.

NOTES ON THE APPLICATION OF FREQUENCY SYNTHESIZERS

IN THE digital frequency synthesizer we have a frequency standard whose output frequency can be selected by either manual or electronic command to very high resolution in less than a millisecond. Such an instrument constitutes a most powerful tool. In communications work, for example, the synthesizer's excellent spurious-frequency performance makes it well suited to use as the master oscillator in a transmitter and as the local oscillator in a receiver. If the transmitter and the RF section of the receiver are untuned, an extremely fast switching system can be used to change the local oscillator (synthesizer) frequency to achieve communications systems of high integrity.

Again, the synthesizer can greatly facilitate surveillance work if it is used as the local oscillator in a receiver* designed to accurately determine the frequency of remote transmitters. The ease and speed with which the synthesizer frequency can be changed will allow monitoring of a multiplicity of channels with a single receiver by sequencing the local oscillator (synthesizer) through the desired channels.

Sequencing the synthesizer output through a group of desired frequencies can also permit a single instrument to operate as an automatic calibrator for a multiple-frequency setup such as a multiple-transmitter installation. The arrangement can provide for phase-locking the transmitter frequencies to the synthesizer by a circuit with a time constant long enough to maintain the transmitter frequency for the duration of the sequencing cycle.

In HF communications work, dependable long-distance communications requires the use of a frequency near the maximum usable frequency, which is determined by ionospheric conditions. Since these conditions can change rapidly, test transmissions over the HF spectrum are used at frequent intervals to insure loop operation. The fast switching and electronic control of the synthesizer make it a natural part of such a "radio sounding" system.

*In receiver work a double-balanced mixer is recommended since it will discriminate against spurious responses and will further improve the effective noise level.

MICROWAVE/SPACE COMMUNICATIONS

The effective use of the microwave spectrum for communications requires frequency sources having extremely good fractional frequency-stability so that the receiver bandwidth can be minimized. With a 3 kc information bandwidth at 10 kMc, a frequency stability of 3 parts in 10^8 for the duration of a message is desirable for double-sideband work. For single-sideband work the requirement is about 1 part in 10^9 for the same conditions. Obviously, a synthesizer must be used in such a communications system to make it practical. The high spectral purity of the synthesizer permits multiplication of its output even to X-band with a signal-to-noise ratio ample for such applications.

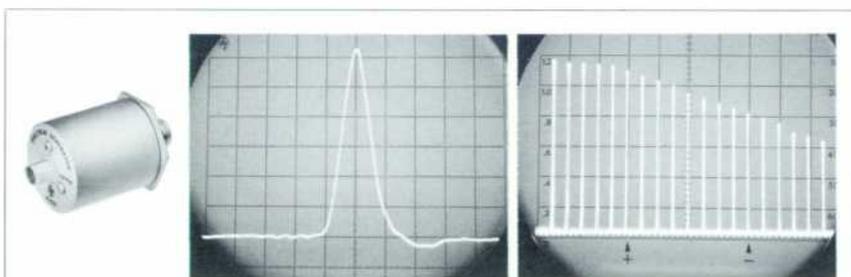
Determining the velocity of far-out space vehicles through Doppler frequency measurements involves operation at X-band with receivers having IF bandwidths of but a few cycles to minimize noise levels. As the vehicle velocity changes, the receiver's local oscillator

frequency must be changed to keep the received signal in the center of the IF bandwidth. Here again, the synthesizer is ideal because of its stability and because its frequency can be changed in known and selectable increments.

AUTOMATIC TESTING

Fig. 2 in the accompanying article shows the amplitude response of a narrow-band crystal filter plotted automatically in permanent-record form. Fig. 4 of that article shows the system used to make the record. The system provides for either manual change of frequency or automatic change of frequency under the control of a simple tape-operated programmer. Under automatic operation, a point is plotted automatically as soon as the X-Y plotter's positioning servos null. The programmer is then commanded to advance to the next test point. Where the response is a slow function of frequency, the programmer dictates relatively large steps in frequency. Where the response changes rapidly, small frequency steps are made.

This same type of system could be used for plotting the in-band phase response by substituting a leveler and phase comparator for the amplifier indicated in the diagram.



SPECTRUM EXTENSION TO ABOVE 500 MC

Many readers will find in the accompanying oscillograms an unusual and excellent example of a time-frequency transform pair. The oscillograms are the more unusual, however, in that they are actually of times and frequencies in the nanosecond-kilomegacycle region. They were made possible by the use of the -hp- 185B Sampling Oscilloscope and a new -hp- Spectrum Analyzer soon to be described.

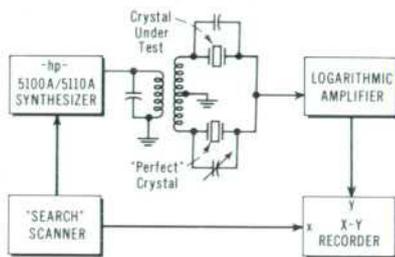
In addition to their technical interest, though, these oscillograms demonstrate how the frequency output of the new synthesizer can be extended to at least 500 Mc through the use of a simple spectrum generator. The generator is a passive device which can be driven directly from the synthesizer.

The time-plot oscillogram shows the output pulse typically produced by the generator when driven from the synthesizer. The pulse has the same repetition frequency as the synthesizer frequency, in this in-

stance 50 Mc. The pulse amplitude here is about a volt and the width about one nanosecond. Width is essentially independent of driving frequency, which can range down to 10 Mc.

The generator's corresponding frequency spectrum is shown from 50 Mc to 1000 Mc in the second oscillogram. The amplitude of the components varies from about 75 millivolts at the 50 Mc component to about 2.5 millivolts at the 1000 Mc component, measured across a 50-ohm load. The spectrum is not rated above 500 Mc, although a 1000 Mc spectrum is shown here and usable outputs to 2000 Mc are usually available.

Being harmonics of the synthesizer's frequency, the generator's output frequency components have the full precision and stability of the synthesizer. Further, their resolution is reduced only by the number of the harmonic used. Even at 500 Mc, then, harmonics can be adjusted in 0.1 cps steps by changing the synthesizer's 50-Mc output in 0.01 cps steps. Commercial band-pass filters are available to select a desired harmonic range from the generator.



Arrangement for plotting spurious modes in crystals.

A similar automatic arrangement could be used for testing and sorting frequency-sensitive components with great precision and speed.

SPECTRUM ANALYSIS/NMR

The ability of the synthesizer to provide a signal of extremely high frequency stability, when coupled with the fineness of resolution provided by the instrument, greatly facilitates analysis of spurious modes in resonant devices. A setup for plotting spurious modes in quartz plates is shown in the accompanying illustration. The arrangement shown allows observation of modes which are very close to the main response mode and which are 60 to 70 db down.

Nuclear magnetic resonance methods are increasingly used to determine, among other things, the qualitative and quantitative make-up of materials. In this method the strength of an applied dc magnetic field and the frequency (usually 2 to 100 Mc) of a simultaneously-applied RF field needed to produce a nuclear resonance in the material must be known. The dc magnetic field can be controlled at a defined reference value with great stability by previously-developed means. The synthesizer now

provides the RF excitation frequency at the high precision needed to greatly enhance the precision of NMR measurements. The ease of frequency control in the synthesizer allows for automatically testing for the presence and quantity of several elements in a sample and does so with such speed as to make NMR in-process control a real possibility.

Lastly, a most interesting case is the use of the synthesizer in the examination of the atomic spectral lines of a cesium beam tube.*

FREQUENCY AND LEVEL STABILITY MEASUREMENTS

The excellent frequency stability of the synthesizer can be used as a standard in measuring the frequency stability of other signal sources. In frequency-stability measurements, the synthesizer signal can be subtracted from the signal under test, thereby translating instabilities to a lower frequency where they can be measured by a frequency counter, low-frequency analyzer, or other means.

It is also interesting to note that the synthesizer can be used in measuring the phase stability of such devices as IF amplifiers, frequency multipliers, frequency dividers, trigger circuits, and resonant devices. In such work a phase comparator is used to synchronously mix the input signal (supplied by the synthesizer for stability) and the output signal of the unit under test. By adjusting the phase of the signals to a quadrature relation, any phase perturbations introduced by the unit under test will be readily observable at the comparator

output. This technique is very sensitive and powerful and can be used as a measure of the reliability of the device under test even if the phase stability itself is not of special importance.

Measurements involving the calibration of voltmeters, power meters, and attenuators must depend on a signal source with high stability of output level. The level stability (typically 0.01% over a few-minute period) of the synthesizer is about an order of magnitude better than that available from high-quality generators operating on a regulated power line.

For versatile coverage from 50 to 500 Mc the *hp-10511A* Spectrum Generator accessory shown elsewhere herein can be used to provide more than 25 mv at any desired frequency over this range. Fixed or tunable filters are commercially available to eliminate the undesired harmonics of the output spectrum.

hp's Dymec division has a system available for tunable coverage over the range from 0.8 to 12.4 Gc using microwave oscillators phase locked to harmonics of the synthesizer's output frequency.

The synthesizer phase noise and spurious signals will be deteriorated by at least the harmonic multiplication factor in any frequency multiplication scheme. Parametric harmonic generation in particular must be carefully evaluated.

GENERAL

The performance and versatility of the new synthesizer are such that it is reasonable to expect that many new and significant applications will come to light as scientists and engineers contemplate the potentialities of this system.

—Victor E. Van Duzer

*Leonard S. Cutler, "Examination of the Atomic Spectral Lines of a Cesium Beam Tube with the *hp-10511A* Frequency Synthesizer," *Hewlett-Packard Journal*, Vol. 15, No. 4, December, 1963.

SYNTHESIZER DESIGN LEADERS



Victor E. Van Duzer



Hans H. Junker



Theodore G. Pichel



Walter R. Rasmussen



Alexander Tykulsky

Vic Van Duzer joined *hp-* in 1958 as a development engineer. He worked on the *hp-* sampling oscilloscope, later became group leader for the initial work on the *hp-* 215A Pulse Generator. For the past three years he has been the section manager for the frequency synthesizer. He holds a BSEE from the University of Illinois, an MSEE from Stanford, and has received patents with others pending.

Hans Junker joined *hp-* in 1960, working on the development of the 104AR and other frequency standards. He was group leader for the driver section of the frequency synthesizer and is presently group leader of the Atomic Standards group. He holds a BSEE and MSEE from

the University of California, is a member of Eta Kappa Nu, Tau Beta Pi, Sigma Xi, and Phi Beta Kappa.

Ted Pichel joined *hp-* in 1956 and has worked as a product design engineer on *hp-* digital recorders, the *hp-* delay generator, frequency standards and on the new synthesizers. He received a B.E. in mechanical engineering from Yale University and has done engineering in the aircraft field on jet and missile equipment. He holds patents and has others pending.

Wally Rasmussen joined *hp-* in 1958 and was assigned to an investigation project on frequency synthesis. Since 1961 he has been

actively engaged in the design of the new synthesizer and was group leader for the low-frequency section of the synthesizer. He holds a B.S. in Engineering Physics from the University of British Columbia, an MSEE from Stanford.

Al Tykulsky joined *hp-* in early 1962 as group leader for the UHF section of the new synthesizer. He has had experience in the design of multichannel FM and radio-relay equipment, in UHF circuitry for TV, and prior work in the design of VHF and UHF synthesizers. He has a BSEE from CCNY and an MSEE from Rutgers, and has patents relating to SSB generation, duplex communications, a pattern generator, and a sweeping oscillator.