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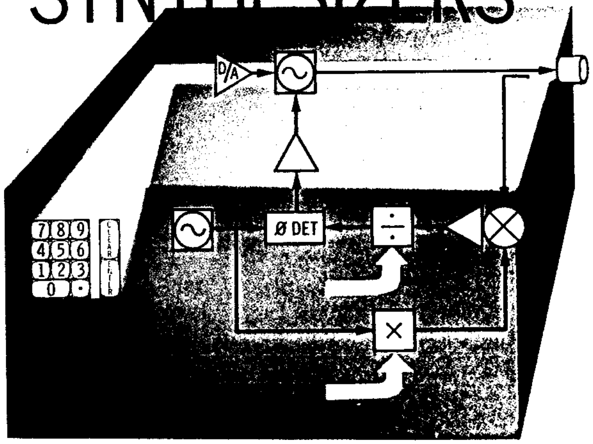
Vol. 2 No. 3 May/June 1975

Tech-notes

MICROWAVE FREQUENCY SYNTHESIZERS

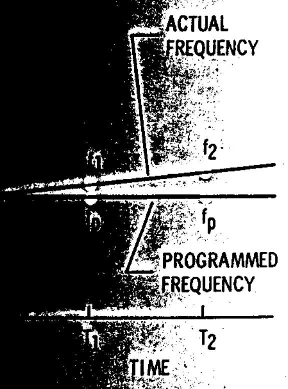


Accuracy and Purity...Quickly and Easily

Microwave equipment performance requirements are continually becoming more stringent. This is especially true of requirements relating to frequency performance, such as, frequency accuracy, spectral purity and tuning or switching speed (under digital control). Even at frequencies as high as 12, 18 and 26 GHz, an accuracy of 1 MHz or better is often required. Signal purity approaching that of the cavity tuned oscillator, with its narrow electrically tuneable frequency range, is often a necessity. But, when equipment size and weight are to be maintained or reduced by 50%, frequency range is to be increased by 200% and frequency is to be controlled by a computer or from a remote location—it is apparent that such increased requirements do not make the solution a simple one.

As a part of the solution to these growing demands, microwave frequency synthesizers have made great strides during the early 70's, and have become more readily available to the growing microwave community.

This article discusses both the direct and indirect frequency synthesizer in the 500 MHz—18 GHz (and higher) frequency range. The theory and applications presented will assist the reader to consider and evaluate his alternatives when confronted with the requirements for high frequency accuracy and signal purity, ease and speed of changing frequency, and remote or automatic control.



PERFORMANCE	INCREMENT	RATIO
FREQUENCY ACCURACY		
1) AT T_1	$\|f_1 - f_p\|$ Hz	$\|f_1 - f_p\| / f_p$
2) AT T_2	$\|f_2 - f_p\|$ Hz	$\|f_2 - f_p\| / f_p$
FREQUENCY REPEATABILITY OVER T_1 TO T_2	$\|f_2 - f_1\|$ Hz	$\|f_2 - f_1\| / f_p$
FREQUENCY STABILITY (OVER CONSTANT TEMPERATURE)	$\frac{\|f_2 - f_1\|}{T_2 - T_1}$ Hz PER UNIT TIME	$\frac{\frac{\|f_2 - f_1\|}{T_2 - T_1}}{f_p}$ PER UNIT TIME

Frequency Accuracy, Repeatability and Stability performance criteria.

Essential Characteristics

Although microwave frequency synthesizers differ from lower frequency synthesizers in the areas of complexity, design techniques and cost, there are similarities common to both. In general, the synthesizer signal exhibits a high degree of frequency stability and spectral purity which is proportional to the internal or external reference oscillator employed. In addition, the synthesizer is characterized by the ability of its output frequency to be digitally programmed. Other pertinent synthesizer parameters are minimum programmable frequency resolution, output power, manual control capability, and performance under severe environmental conditions. Occasionally, the speed of changing frequency may dominate the decision between the two basic synthesizer types.

Synthesis Methods—Direct and Indirect

As suggested, there are two basic techniques of frequency synthesis—direct and indirect. The direct synthesis method relies on the algebraic manipulation of existing signal frequencies to produce the desired output frequency. This method provides extremely high switching speed among the available output frequencies. The switching speed is normally less than 100 μsec and can be so fast that it is difficult to measure directly.

Indirect synthesis is achieved through the use of phase-lock loops between a microwave frequency oscillator and a lower frequency reference oscillator. The switching speed or, more appropriately, the lock-up speed of the indirect synthesizer (>100 μsec) is slower than the direct synthesizer, but cost, spectral purity and greater availability counteract the difference in switching speeds for most applications.

Performance Criteria

In order to discuss the synthesizer operation and performance, it is useful to clarify the terminology to be used. Terms such as frequency accuracy, frequency repeatability and frequency stability are often misunderstood or, more often, used interchangeably when applied to synthesizers. Figure 1 shows a curve of frequency versus time which can be used to distinguish the meaning of each.

- Frequency Accuracy is the frequency difference between the actual synthesizer output frequency (f_1 or f_2) and the programmed frequency (f_p). Absolute frequency accuracy (or inaccuracy) is expressed as $|f_1 - f_p|$ Hz at a time t_1, or $|f_2 - f_p|$ Hz at a different time t_2. Frequency accuracy also may be expressed as the ratio of absolute frequency difference to programed frequency, $\frac{|f_1 - f_p|}{f_p}$. Because of the synthesizer's high accuracy, measurement of the actual frequency should be performed with quality instrumentation traceable to the National Bureau of Standards.
- Frequency Repeatability is the difference between actual frequencies measured at two different times for a single value of programmed frequency. No absolute accuracy is implied, only the change in frequency, $|f_2 - f_1|$ Hz, or as the ratio, $\frac{|f_2 - f_1|}{f_p}$, over an identified time period.
- Frequency Stability is the drift rate of the synthesizer output frequency over time and/or change in temperature. The rate may be expressed as $\frac{|f_2 - f_1|}{t_2 - t_1}$ Hz per second, hour, day or month, or as an incremental change in Hz per temperature range. It also may be expressed as a ratio of frequency drift rate to the programmed frequency, such as, $\frac{\frac{|f_2 - f_1|}{t_2 - t_1}}{f_p}$ per unit of time.
- Spectral Purity describes the aggregate distortion from noise, nonharmonic spurious signals and harmonically related signals. The degree to which the actual frequency spectrum deviates from the ideal spectrum is an assessment of the synthesizer's spectral purity, and is shown in Figure 2. Noise results from the random amplitude and phase fluctuations of the signal with time. It causes a broadening (or diffusion of power) of the signal. Since phase fluctuation (or short-term frequency instability) is normally the major contributor to noise in microwave synthesizers, noise is often referred to as phase noise only. The power associated with true random noise is proportional to the measurement bandwidth. This, as well as the offset frequency from the desired signal, must be considered when evaluating synthesizer noise specifications.

Nonharmonic spurious signals (or "spurs") result from coherent (sinusoidal) fluctuations of the signal's amplitude or phase over time. Their frequency is not a multiple of the signal center frequency. These "spurs" may be caused by an undesired modulation of the oscillator signal, mixer intermodulation products, or by an abnormality within the oscillator itself. Quality oscillators and systems normally will not produce significant spurious signals.

Harmonically related signals (or "harmonics") exist at frequencies which are integer-multiples of the oscillator center frequency. They result from distortions in the oscillator output waveform which cause it to depart from a pure sinusoidal shape.

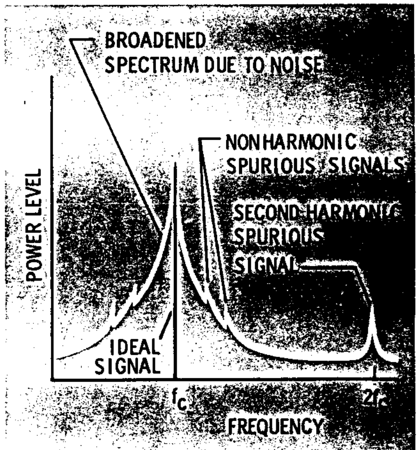
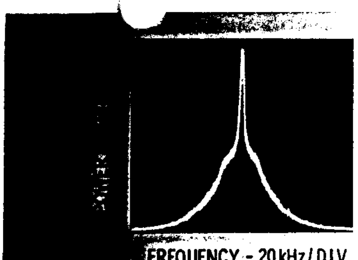


Fig. 2. Broadened frequency spectrum of the desired signal at frequency f_c by noise, with nonharmonic and harmonic spurious signals.



A Spectrum Analyzer presentation of a synthesized signal centered at 12.0 GHz. The frequency spectrum is that of the WJ-1250/1251-5 Indirect Frequency Synthesizer. The Spectrum Analyzer measurement bandwidth is 1 kHz.

These distortions are created by inherent nonlinearities in the oscillating elements themselves (transistors and Gunn-effect diodes).

In an actual spectrum analyzer presentation of a 12 GHz signal, Fig. 3, power due to noise is shown to drop off rapidly at low-offset frequencies from the center frequency, and nonharmonic spurious signals are suppressed by greater than 60 dB below center frequency power. Of course, any harmonically related spurious signal would exist out of the display range.

- Switching Speed or Program Response Time is the time from the introduction of a new programmed command to the completion of the resulting frequency change. The ability to respond quickly to digitally programmed frequency changes makes both synthesizer types valuable in computer controlled and other automatic applications. For applications that require extremely rapid frequency switching, switching speed becomes the delineator between the two synthesizer types.

Direct Synthesis

An example of a basic direct synthesizer is shown in Figure 4. Multiples of the reference oscillator frequency are generated in a harmonic generator and are then selected by individual band-pass filters, followed by amplifiers. In this example, a set of ten harmonics is selected from the Nth to the (N + 9)th. The ten frequencies—all harmonics of the reference oscillator—are fed into a switch matrix. Switch matrix output frequencies, Fx and Fy, are selected by two logic word inputs to the matrix: Fx is selected by the first frequency select word and Fy by the second select word. The Fx output is fed directly to a mixer. The Fy frequency output is first divided by 10 and then fed into the mixer's second input port. The mixer I-port provides the synthesizer output Fx + Fy/10, which may be equal to any one of a 100 programmable frequencies. This scheme may be easily expanded to produce larger numbers of programmable frequencies.

The frequency stability of the output signal is derived directly from the reference oscillator's stability. The synthesizer's spurious performance, however, is dependent on the particular scheme chosen and on other design parameters such as filter specifications, switch matrix isolation and mixer intermodulation characteristics. Because many different frequencies are present simultaneously in the direct synthesizer, suppression of spurious products presents a difficult design problem. The only desired frequency output is Fx + Fy/10; however, the mixer output signal can include any frequency given by the equation KFx ± LFy/10, where K and L are integers. It is the filtering and switching of the input signals to the mixer and the minimization of any mixer products which represent the most critical areas of the design. Another design problem of the direct synthesis method is the prevention of radio frequency interference (RFI) from the many frequencies existing within the synthesizer.

Switching time between any two of the one hundred possible frequencies is dependent upon the response time of the switch matrix. This response time can be made very short, thus switching times of practical direct synthesizers may be in the low microsecond time range (<100 μsec).

To generate frequencies in the microwave range, direct synthesis is normally performed at lower frequencies (as illustrated in Figure 4), and then multiplied or up-converted. A single multiplication is easier, and usually the preferred method when the output range is relatively narrow, Fig. 5a. In order to cover wide frequency ranges, however, up-conversion by mixing against stable single-frequency microwave signals is usually employed, Fig. 5b. These

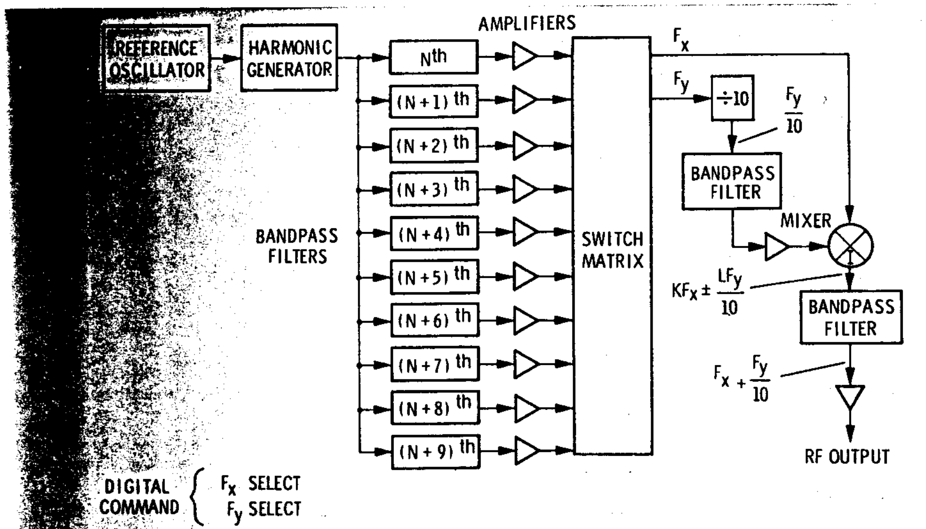
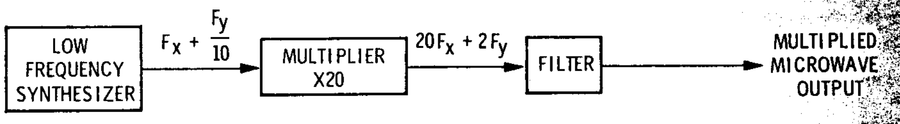
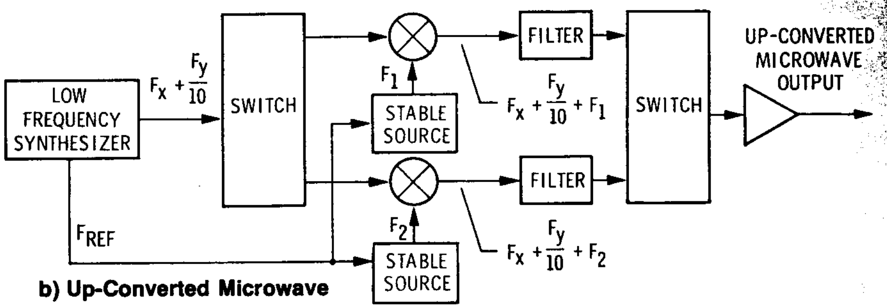


Fig. 4. A basic Direct Frequency Synthesizer with a RF output equal to any one of 100 programmable frequencies.



a) Multiplied Microwave Output.



b) Up-Converted Microwave Output.

Fig. 5. Directly synthesized microwave frequency generation by a) multiplying and, b) up-converting the lower frequency direct synthesized signal, $F_x + F_y/10$.

single-frequency stable signals are also derived from the basic reference oscillator. Either method, or a combination of both, will preserve the fast switching speed of the direct synthesizer, but with increased complexity, size and cost.

This complexity—the large quantity of amplifiers, mixers, multipliers and filters within the dirrect synthesizer—will generally cause it to be more expensive and larger than a comparable indirect microwave synthesizer. In addition, the direct synthesizer is likely to contain many RF circuits requiring periodic alignments. The multiplication to microwave frequencies also causes degradation in phase noise performance which may be undesirable in low phase noise applications.

Indirect Synthesis

An indirect synthesizer is illustrated in Figure 6 and centers around a voltage-controlled oscillator (VCO). In this example, the voltage controlled oscillator (VCO) is first tuned as close as possible (0.1 to 1%) to the programmed frequency command. This "coarse" tuning is accomplished by a digital-to-analog (D/A) conversion of the incoming digital frequency command.

A second "fine-tune" correction is then applied to the VCO in order to achieve greater accuracy and stability. This fine-tune correction is a feedback signal and is obtained as follows. The VCO's output frequency is first mixed against a selected multiple of the reference frequency, and the difference frequency is amplified and divided by "N" in a programmable digital divider. The divided-down frequency is then compared to the reference, and an analog signal proportional to any phase difference is fed back to the VCO as the fine-tune correction. Since phase comparators are most commonly used for generating the feedback correction signal, the frequency control feedback loop is referred to as a phase-lock loop. The open-loop gain and bandwidth of the phase-lock loop determine how closely the VCO output stability reproduces the reference signal stability. The performance of the indirect synthesis method, therefore, is greatly dependent on the phase-lock loop design.

A YIG-tuned oscillator (YTO)* is normally used as the VCO because of its high Q (300 to 800, loaded), octave-band or greater frequency coverage, good linearity (±0.1 to 0.3%) and solid state construction. An added feature is the availability of two tuning coils—a main coil and an FM or Fine Tune Coil—for YTO tuning. These two coils eliminate the need for coarse and fine-tune summing circuitry. Varactor-tuned oscillators are sometimes used when a greater tuning rate is necessary and lower values of "Q" and linearity can be tolerated.

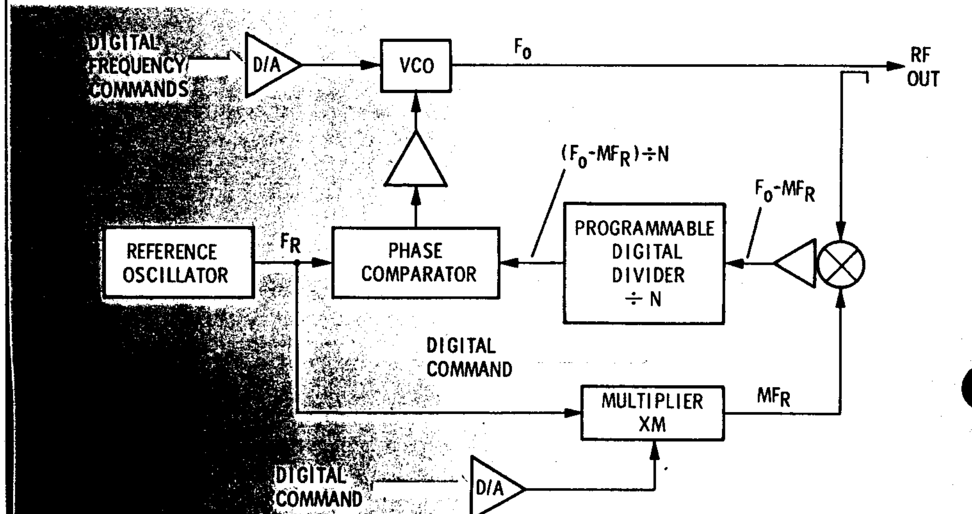


Fig. 6. A basic Indirect Frequency Synthesizer with frequency control feedback loop.

Spurious signals in indirect synthesis are generally much more easily controlled than in direct synthesis. The only significant nonharmonic spurious signals appearing on the VCO output are from the frequency products which fall within the relatively narrow phase-lock loop bandwidth. Consequently, this limited frequency range of susceptability eases the spurious suppression design requirements.

Harmonics of the VCO fundamental frequency are generally larger in magnitude than the nonharmonic spurious signals (in the order of −15 to −20 dB versus −60 dB). This does not create a significant problem at microwave frequencies since the harmonics are far removed from the fundamental frequency and, if necessary, may be easily reduced by filtering.

When the output of an indirect synthesizer changes to a new programmed frequency, the VCO must slew to the new frequency and then lock up. Therefore, the switching time is dependent on the VCO's tuning rate and the response time of the loop. This switching time can be made relatively low (100 μsec) by using a fast tuning VCO, but it is still considerably slower than switching between existing signals of the direct synthesis method. For this reason, indirect synthesizers are generally limited to applications allowing switching times greater than 100 microseconds.

Both direct and indirect synthesizers have been built to cover the microwave region; however, it is the indirect microwave synthesizer which dominates the field. First, indirect synthesizers are generally lower in cost. An exception to this may be in a narrow-band, specialized application where a direct synthesizer could be less costly.

Secondly, the indirect frequency synthesizer offers a lower level of phase noise, a major consideration at microwave frequencies. Figure 7 illustrates the relative phase noise for both synthesizer types. The phase noise of the direct microwave synthesizer first decreases as the offset frequency is increased from center frequency. This performance is characteristic of the multiplied-up reference signal. As the offset frequency is increased further, however, the thermal noise of the amplifiers and multipliers dominate, and the phase noise flattens out and may even start to increase.

In the indirect synthesizer, the phase-lock loop transfers the characteristics of the multiplied-up reference to the VCO within the loop bandwidth. As the offset frequency approaches the loop bandwidth, the inherent VCO phase noise begins to

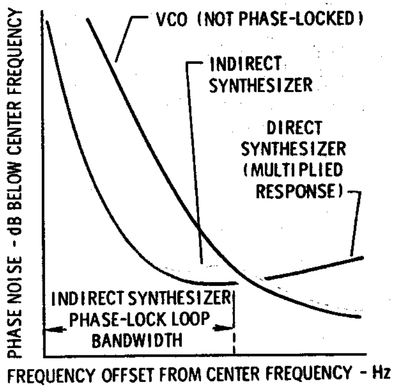


Fig. 7. Phase noise characteristics of direct and indirect frequency synthesizers.

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*The YIG-tuned bulk GaAs oscillator is the subject of the Sept/Oct 1974 issue of dominate. At frequencies beyond the loop bandwidth, the phase-lock loop has no effect, and the performance is that of the VCO only. Thus, the indirect synthesizer combines the best features of both the better close-in performance of the multiplied-up direct synthesizer and the better far-out phase noise of the VCO.

A third advantage of indirect synthesis is an output power of 10 mW or higher up to 18 GHz, with all solid state construction. To obtain an equivalent output power from a direct synthesizer that covers a wide frequency range, would require additional amplifiers, including a TWT amplifier above 12.4 GHz. As a result, the direct synthesizer would be even larger, heavier and consume more power. The W-J Model 1250 Indirect Synthesizer, Fig. 8, is an example of a general purpose synthesizer covering 1 to 18 GHz. Other 1250 configurations can cover all or portions of the 500 MHz to 26.5 GHz frequency range. Frequency may be programmed manually via the front panel keyboard with LED display or digitally through a rear panel connector.

Nature of Synthesizer Applications—Direct and Indirect

Frequency synthesizers are used where one or more of their performance characteristics justify the cost premium over unsynthesized signal sources. Major applications are in automatic test systems, military electronic intelligence and countermeasures systems, and communication systems. Additional applications include calibration, design laboratory, R&D, and scientific activities. In each application, the synthesizer allows the frequency to be changed easily and quickly with greater accuracy and purity of the output signal. The effect is reduced cost of performing desired operations and/or improved quality of the results.

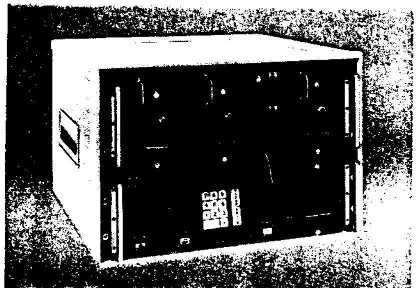

Fig. 8. The WJ-1250 Microwave Frequency Synthesizer configured to cover the 1 to 18 GHz frequency range. Actual size of this configuration is 12.25 × 19 × 22 inches.

One of the fastest growing applications of microwave synthesizers is automatic test systems. Here the synthesizer provides the stimulus, and in some cases a reference frequency against which the manipulated stimulus may be down-converted. The use of the synthesizer permits rapid programming of a highly accurate stimulus by computer control. The importance of rapid programming is especially evident in complex and expensive systems where test time should be held to a minimum. A prime example is the automatic testing of electronic systems in aircrafts, ships and other similar system platforms. The accuracy and repeatability of the measurement gives a greater depth to the test program, thereby enabling the user to test for "fine grain" characteristics to more completely characterize the unit or system under test. Similarly, test speed is important to achieve a labor reduction in the testing of less complex frequency sensitive products.

Microwave automatic test systems often need frequency accuracies of better than 100 KHz. This translates to 5.6 parts per 10^6 if an 18 GHz maximum test signal frequency is assumed. This frequency accuracy is easily accomplished by a synthesizer with frequency stability specifications of 1 part per 10^9/day and ±5 parts per 10^8 over 0°C to +50°C. For example, during a 180 day calibration period the synthesizer's maximum error would be $[(1 \times 10^{-9}/\text{day} \times 180\ \text{days}) + 5 \times 10^{-8}]$ or 2.3 parts per 10^7. However, for a guaranteed error of less than 1 KHz over the same 180 day period, the required frequency stability over time and temperature should be equal to or better than 2 parts per 10^{10}/day and ±5 parts per 10^9 over 0°C to +50°C, a difficult but achievable performance by a synthesizer with internal reference. Increased performance also can be provided by using an external reference signal input to the synthesizer.

A second application of microwave synthesizers is military microwave electronic intelligence and countermeasures (ECM) systems. A major portion of the intelligence systems consist of reconnaissance receivers. These receivers often employ the superheterodyne technique of beating an incoming RF against a local oscillator (LO) to produce the desired IF. Because any frequency inaccuracy or undesirable modulation of the LO signal will appear in the IF, the LO should be more accurate and spectrally purer than the incoming RF signal to be analyzed. For this reason, a synthesized signal is often used as the LO where the required increased accuracy of the analyzed RF signal justifies the cost of the synthesizer.

In such superheterodyne reconnaissance receivers used for high quality signal analysis, wide frequency coverage, frequency accuracy and spectral purity of the LO are the major requirements. Switching speed is normally somewhat less important. Thus, the indirect synthesizer is normally chosen due to its lower total cost, size and weight. In some instances, instead of using an indirect synthesizer with a receiver containing an existing LO, it may be more practical to phase lock the receiver LO with an external synchronizer. The synchronizer is essentially an indirect synthesizer with its VCO located in the receiver. In this application, a sample of the receiver LO signal is provided to the synchronizer, which in turn, provides a correction feedback signal to phase lock the LO at the appropriate offset from the digitally commanded frequency. Figure 9 shows the SN100/WJ1740 LO synchronizer with several WJ-1740 receiver tuner modules.

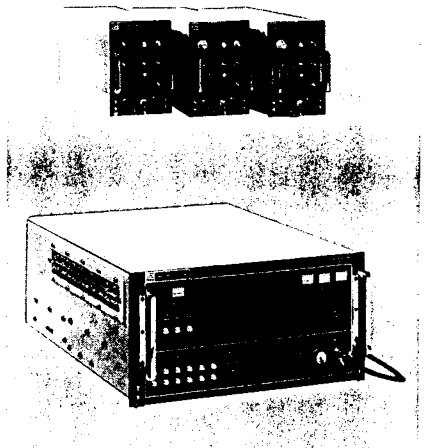

Fig. 9. A SN 100/WJ-1740 LO Synchronizer and three WJ-1740 receiver tuner modules. The synchronizer provides each tuner module with a feedback correction signal to phase lock its LO.

In many ECM systems, the time to change to another threat frequency is of utmost importance. In addition, the major threat bands are usually limited to relatively narrow frequency ranges (often identified through the use of reconnaissance receivers.) Under these circumstances, where hostile signals must be accurately identified by the receiver and/or reproduced by the transmitter to minimize jamming and deception power expenditures, the speed and accuracy of the direct synthesizer is of great value.

As an example, a present day ECM system may require that a signal be switched within 25 microseconds after command, from any one frequency to any other frequency in a 2 GHz range, and to an accuracy of 1 part in 10^6. There are current requirements for ECM systems to meet octave-band stepping speeds in the 100 nanosecond range.

Communications systems are a third area in which synthesizers are employed. In both the transmission and reception of communication signals, frequency accuracy and spectral purity are critical. In space communications ground stations, phase-locked klystrons have normally been used. But today's solid-state indirect synthesizers now offer essentially equal accuracy and spectral purity while reducing the time and effort to change frequencies. Some communication systems of a tactical military nature also take advantage of the accuracy and rapid frequency changing capability of either type of synthesizer.

The indirect synthesizer's characteristics of stability and spectral purity makes it useful as a frequency standard at microwave frequencies, and as a precision instrument for laboratory and scientific use. A synthesizer may be used as a primary or secondary reference standard to calibrate counters, wave meters, filters and other frequency selective devices. As a laboratory instrument, the synthesizer may be used in precision measurement set-ups to measure spectral purity, FM and PM deviations. They are also used for chemical analysis through microwave spectroscopy. In applications such as these, where frequency accuracy on the order of 1 part in 10^{10} or better is required, the synthesizer normally must be phase locked to an external reference. A Cesium standard external reference can provide an accuracy of 1 part in 10^{11} (absolute) to the synthesizer microwave output, whereas, a Rubidium standard reference can also provide a very good long-term stability of 1 part in 10^{11} per month.

Conclusion

This issue has discussed microwave frequency synthesizers as available today for many applications which require high frequency accuracy, spectral purity and speed and ease of changing frequencies. As requirements grow and synthesizer development continues, numerous improvements can be anticipated. These improvements include higher frequency coverage, lower cost for equivalent performance, greater spectral purity, reduced size and weight, and increased reliability. Furthermore, many more signal generators having variable power level and modulation capabilities will be synthesized. All of these improvements will of course increase the usage of microwave synthesizers and support even greater improvements.

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Charles holds a B.S.E.E. from Clemson University and a M.B.A. from Harvard University. Mr. Foster is currently Head, Frequency Synthesizer Section of W-J's Space and Support Equipment Department. He is responsible for the design and development of microwave equipment using frequency synthesis techniques, which include: the WJ-1250 modular microwave synthesizer, the SN 100 LO synchronizer and an RF target simulator system, all digitally programmable and covering the 0.5—18 GHz range. Other developments in Mr. Foster's section include an 18—26.5 GHz RF source for the WJ-1250, the WJ-1201 Programmable Signal Generator, the WJ-1189-1 synchronizer and specialized test systems. Mr. Foster was formerly a W-J Applications Engineer for microwave synthesizers and test systems. Charles is a member of the Association of Old Crows.

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