VOL. 14 NO. 4 JULY/AUGUST 1987

How To Specify And Use A DTO/VCO

WATKINS-JOHNSON COMPANY

Tech-notes

Modern EW systems require digitally tuned oscillators (DTOs) for use as local oscillators in receivers and in transmitters for jamming. Using PROM correction circuits, DTOs are now capable of excellent frequency accuracies. In addition, buffer amplifiers following the oscillator are capable of providing power levels in excess of 100 mW (+20 dBm), while reducing frequency pulling to typically less than 1 MHz. Also, voltage regulators internal to the DTO reduce pushing effects under 1 MHz/V.

However, DTOs exhibit several subtle characteristics that may affect system performance, including such factors as the set-on accuracy of a receiver, receiver sensitivity, and the power spectral density of a jammer. This article analyzes these factors and explains how and why DTOs affect such performance parameters.

Receiver Applications

ECM receiver systems are often configured using a double conversion technique, as shown in Figure 1. A signal from 2 to 18 GHz is initially downconverted to a common 2-to-6 GHz band, and then a DTO is used to tune across the 2-to-6 GHz band.

The *set-on accuracy* of this system is affected by inaccuracies from the first L.O., which are relatively small, and the DTO. For the DTO, the frequency accuracy is certainly the most significant factor affecting set-on accuracy. Using digital calibration techniques, the frequency accuracy (nonlinearity and drift over temperature) can be virtually eliminated; however, the effects of post-tuning drift and repeatability must still be considered.

Post-tuning drift (PTD) for a DTO is defined as the shift in oscillator frequency output, as a function of time, after a change in digital input word, as shown in Figure 2, for a 2.6-to-5.2 GHz unit. The effect that causes this variation in frequency out to a few milliseconds after a step change in frequency is related to the temperature variation of the active devices in the oscillator, especially the varactor, and similar effects in the driver circuit. As

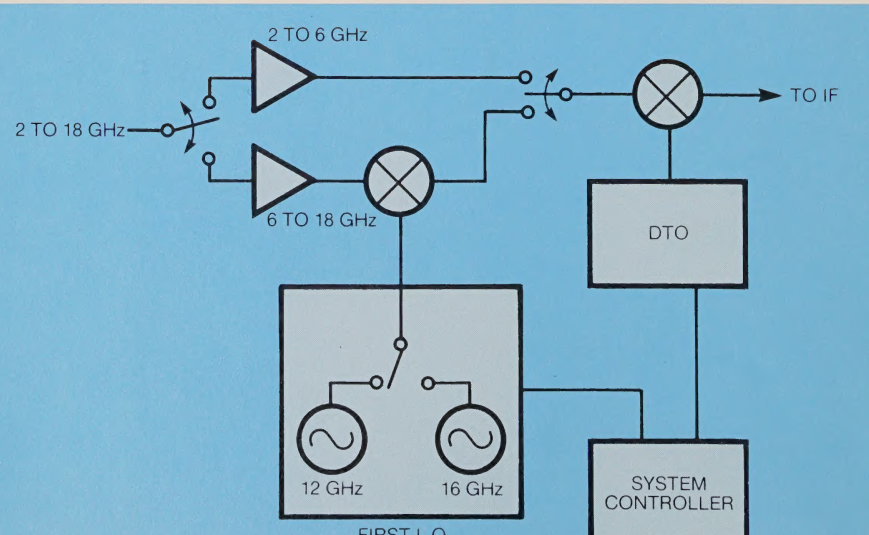


Figure 1. ECM receiver system.

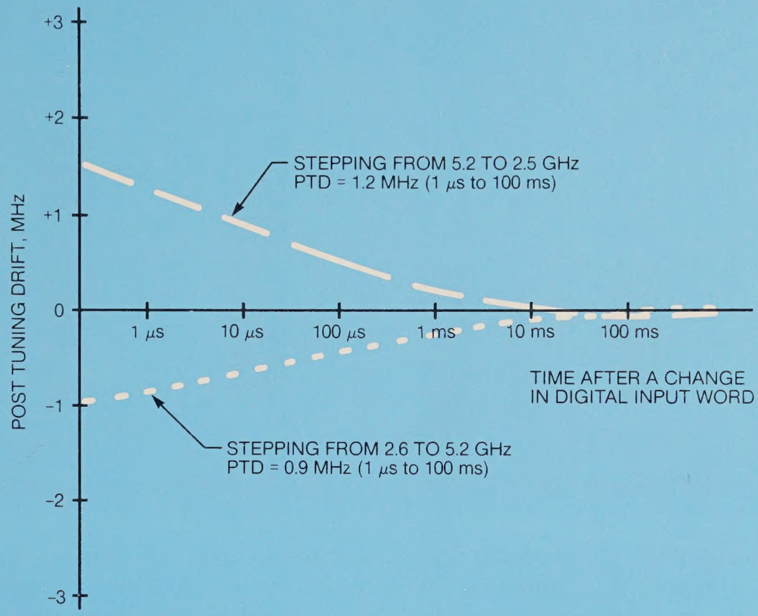


Figure 2. Post tuning drift of a 2.6 to 5.2 GHz DTO.

the oscillator is tuned across the band, its active devices change their operating points due to variations in rf loading; and, as the temperature changes, the impedance changes, causing shifts in frequency. The rate of change of the frequency is associated with the thermal impedances of the active devices in the circuit. The thermal resistance directly affects the magnitude of the drift, and the thermal capacity affects the rate of change of the impedance and, therefore, the rate of frequency change.

Therefore, lowering the thermal impedances of critical active devices and operating them at bias points at which the junction temperatures remain more constant will reduce the PTD. Also, by using lower-power small-signal devices, such as bipolar junction transistors (compared to Gunn diodes), or by use of silicon transistors (compared to GaAs FETs), the PTD can be reduced. A comparison of typical PTD performance for various types of oscillators is shown in Figure 3.

The thermal effects usually end in a few milliseconds; however, DTOs exhibit other longer-term post-tuning-drift mechanisms. These are primarily associated with an effect called "varactor charging," in which ions on the surface of the varactor migrate across the junction over a period of time in the presence of an electric field that is caused by the reverse bias on the varactor. To reduce varactor charging, a special passivation has been developed that forms molecules with these ions so they will not migrate. A comparison of the PTD of a DTO with and without passivated varactors is shown in Figure 4.

The *repeatability* of a DTO defines how well the DTO will return to the same frequency while being switched to that frequency from many different frequencies, as shown in Figure 5, and

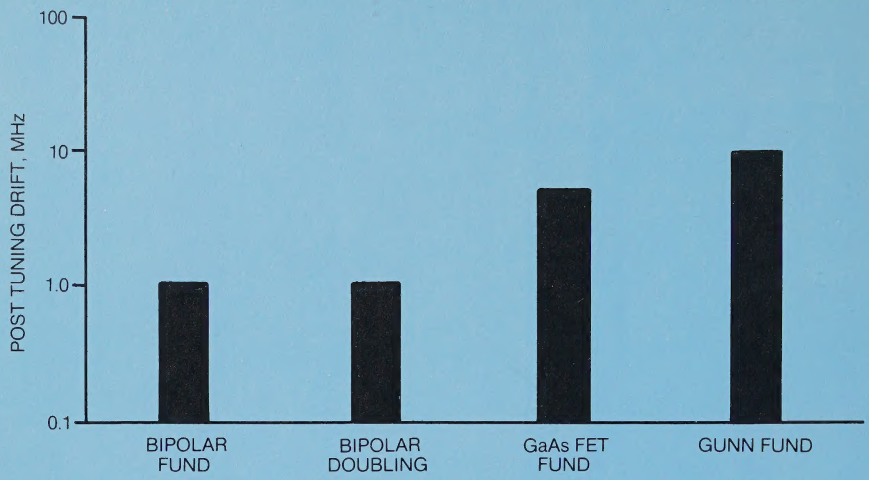


Figure 3. Post tuning drift comparison for various types of oscillator active devices.

includes the effects of post-tuning drift. It is also dependent on how long the DTO rests at either the desired frequency or the other frequencies.

The short-term repeatability (<10 milliseconds) of a DTO can be improved, as is the case for PTD, by reducing the thermal impedances and operating critical active devices like the oscillator transistors and varactors at constant junction temperatures. Long-term repeatability (>10 milliseconds) can be improved by using the previously mentioned specially passivated varactors.

SYSTEM SENSITIVITY

System sensitivity determines the

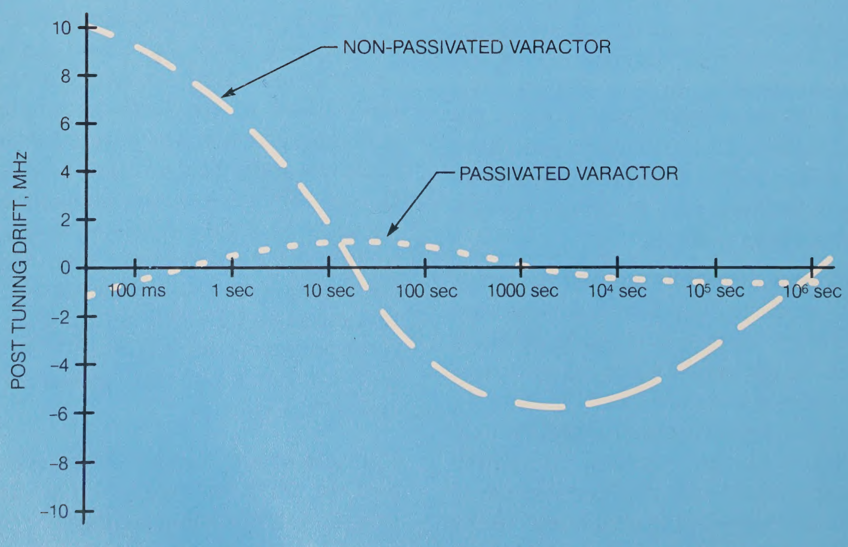


Figure 4. Comparison of PTD with passivated and non-passivated varactors.

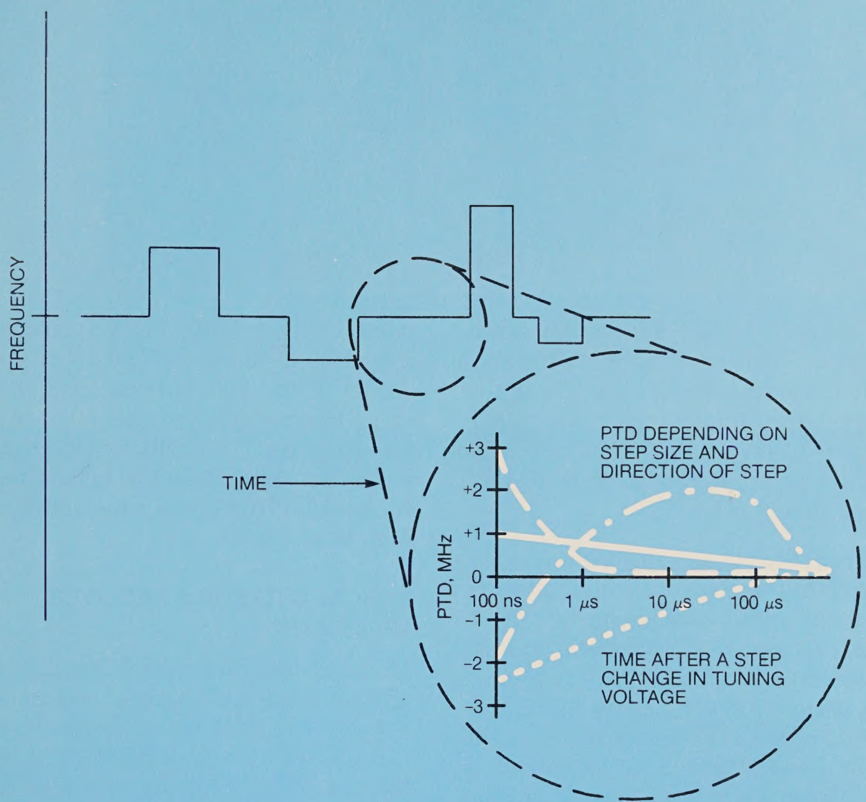


Figure 5. Repeatability.

lowest-level signal that can be received. Certainly, harmonic and spurious signals from the first L.O. and DTO will affect this. However, filtering can normally be used to achieve acceptable results. On the other hand, if the residual fm of the oscillators is too high, it may fill up the receiver IF so signals cannot be detected. The first L.O. residual fm can be made relatively low by using low-noise or phase-locked oscillators. DTOs, however, exhibit greater residual fm, especially when subjected to vibration and bias, and digital line noise.

The *residual fm* of a DTO is defined as the peak-to-peak deviation of the output signal as observed on a spectrum analyzer with a 1-kHz IF bandwidth at -3 dBc. Typically, the residual fm of a DTO using bipolar transistors in the oscillator is less than 100 kHz. This comes from the residual fm of the oscillator itself and the noise from the digital driver that frequency-modulates the oscillator. Gunn diode and FET oscillator DTOs exhibit much worse residual fm, typically 200 to 500 kHz.

Receiver systems normally have a considerable amount of residual fm on the digital and bias lines. It is not uncommon to have 100 mV of noise from power supplies and digital clocks on these lines during normal system operation. This noise causes frequency modulation of the DTO. The normal 100 kHz of residual fm may be degraded to several MHz in the system.

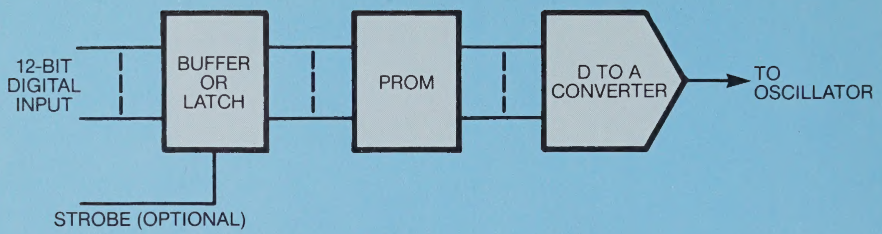


Figure 6. Buffers on digital input.

To reduce the effect of digital-line noise, buffers, latches, or other circuits that attenuate the digital-line noise are added to the digital input, as shown in Figure 6. These circuits can affect the tuning speed, so they must be selected with that in mind.

Bias-line noise also affects the residual fm of the DTO. To reduce this, LC filters may be added, as shown in Figure 7; but, in some cases, it is necessary to add a secondary regulator on the bias input to attenuate low-frequency noise. This has the disadvantage of reducing the voltage available for circuit operation, so the secondary output is used only on the most sensitive bias points. Using digital-line buffering and bias-line filtering, fm levels under 100 kHz can be achieved.

Residual fm in a system during vibration causes parts inside the unit to move. In the oscillator, this causes movement of bond wires and other parts, which results in an increase in the residual fm of the DTO. Careful design of the unit can minimize this effect. For example, the residual fm of a 2.6-to-5.2 GHz DTO exhibits an increase in fm from 100 kHz to 200 kHz, when subjected to 10 g's peak sine vibration from 10-to-2000 Hz.

TYPICAL DTO FOR A RECEIVER APPLICATION

The block diagram of a DTO used in a receiver system is shown in Figure 8. The input to the DTO is driven by a 12-bit digital word to select the desired frequency. Internal to the DTO, a PROM is used to modify the digital address so it exactly matches the oscillator tuning characteristic. Using this technique, frequency accuracies of ±5 MHz can be attained at room temperature, and ±10 MHz can be attained over the -54° to +85° centigrade range. A picture of one of these oscillators covering the 2.6 to 5.2 GHz

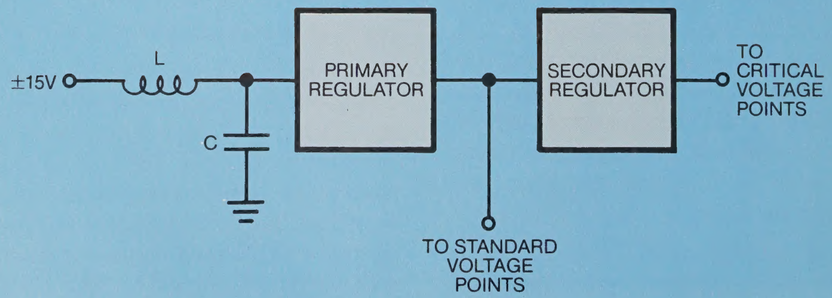


Figure 7. Bias input filter/regulator circuitry.

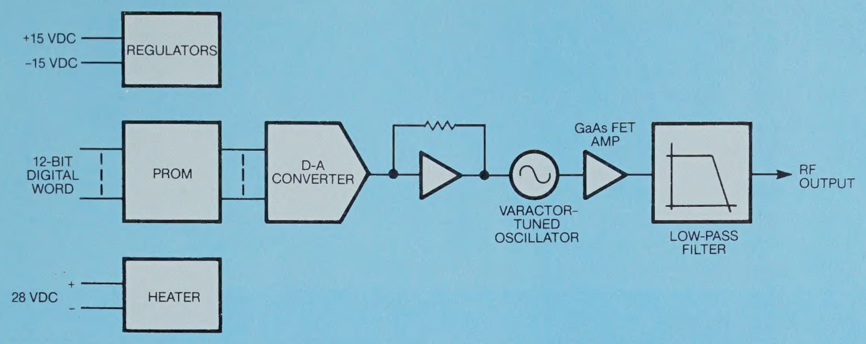


Figure 8. DTO used in a receiver system local oscillator.

frequency range is shown in Figure 9, and the performance characteristics of this unit are summarized in Table I.

Jammer Applications

The digitally tuned oscillator used in a transmitter application is often configured with a modulation port, as shown in Figure 10. In the system, the digital lines are used to set the oscillator on the desired frequency, while the modulation port is used to modulate the oscillator for jamming purposes. As such, the bandwidth of the modulation port needs to be as wide as possible. Typical bandwidths today are in excess of 20 MHz. A picture of one of these

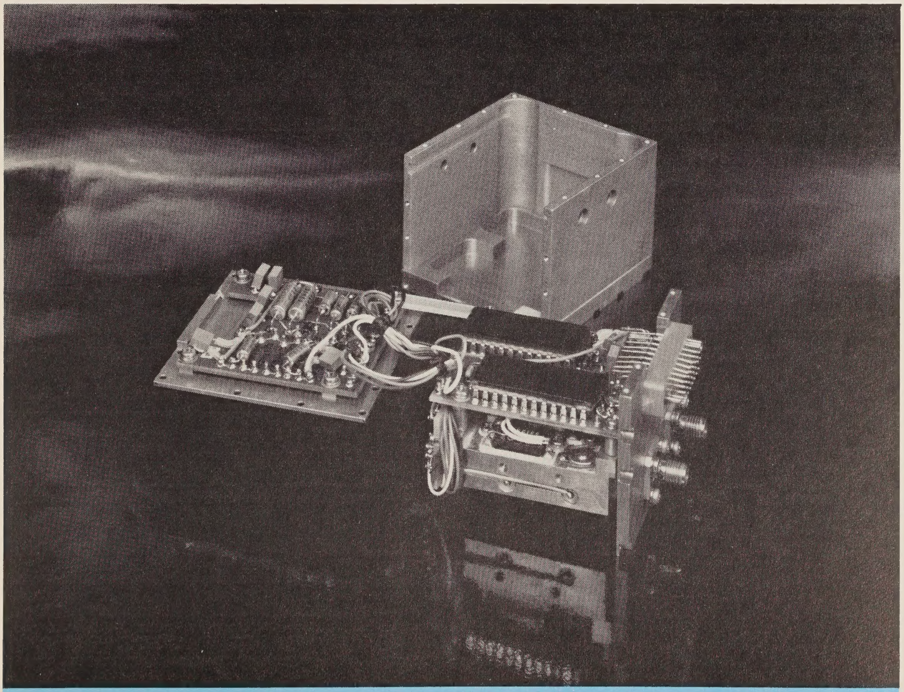


Figure 9. WJ-2854-22 2.6 to 5.2 GHz DTO.

RF Characteristics[1, 2]	Guaranteed
Frequency Range	2.6 to 5.2 GHz
Power Output, Minimum (J1 and J2 Ports)	+12 dBm
Power Output Variation, Maximum (J1 and J2 Ports)	5 dB
Frequency Drift Over Temperature[3], Maximum	0.25 MHz/°C
Spurious Output Suppression	
Harmonic (nf_0), Minimum	–15 dB
In-band, Non-harmonic, Minimum	–70 dB
Pushing Factor, Maximum	1.5 MHz/V
Pulling Figure (3:1 VSWR), Maximum	1.0 MHz
Isolation Between 2 RF Output Ports (J1 and J2), Minimum	15 dB
Tuning Characteristics	
Tuning Resolution	12-bit TTL Compatible
Digital Tuning Range[5]	0 to 4095
Non-linearity[4], Maximum	±18 MHz
Post Tuning Drift (2.5 μsec to 50 μsec), Maximum	1.8 MHz
Post Tuning Drift, 100 msec to 2 minutes	1.0 MHz
Post Tuning Drift, 30 μsec to 100 msec	1.0 MHz
Input Capacitance, Maximum	150 pF
LSB, Maximum	0.9 MHz
Input Power Requirements	
Oscillator Bias[6]	+15 Volts @ 400 mA, Maximum –15 Volts @ 350 mA, Maximum +5 Volts @ 300 mA, Maximum
Heater Voltage[7]	28 Volts
Heater Current at Turn-on	4.0 Amps, Maximum
Heater Current, Steady-state at –54°C	4.0 Amps, Maximum
Environmental Specifications	
Operating Temperature[3]	–54°C to 85°C
Storage Temperature	–62°C to 95°C
Mechanical Specifications	
Package Dimensions Excluding Connectors and Mounting Flanges (LxWxH)	2.12 x 2.28 x 1.73 inches
Weight, Maximum	9.0 ounces
RF Output Connector (both ports)	SMA Jack
Tuning Input Connector	Multi-pin connector (RFI Protected)
Bias and Heater Connections	Multi-pin connector (RFI Protected)
W-J Outline Drawing Number	337758

Notes:

1. The WJ-2854-22 is an rf oscillator employing varactors, bipolar transistors and field-effect transistors as the active elements. It also contains the following interface elements: isolation amplifier (active isolator), voltage regulator, proportionally controlled internal heater, D/A converter, PROM, and linearizer.
2. Unless otherwise noted, performance is specified for operation into a nominal matched load (VSWR ≤1.2:1) at laboratory ambient temperature.
3. Temperature is measured on the oscillator mounting surface.
4. The tuning non-linearity is the maximum deviation from linear tuning between the specified tuning word extremes and includes the effect of frequency drift over the operating temperature range.
5. The digital tuning range specifies the maximum range required to tune from minimum to maximum frequency.
6. Protective circuitry guards against damage due to overvoltage (up to 10 percent) and transient reverse voltages.
7. The heater is a self-regulating, proportionally controlled unit, isolated from bias and signal grounds.

Table I. WJ-2854-22 digitally tuned oscillator.

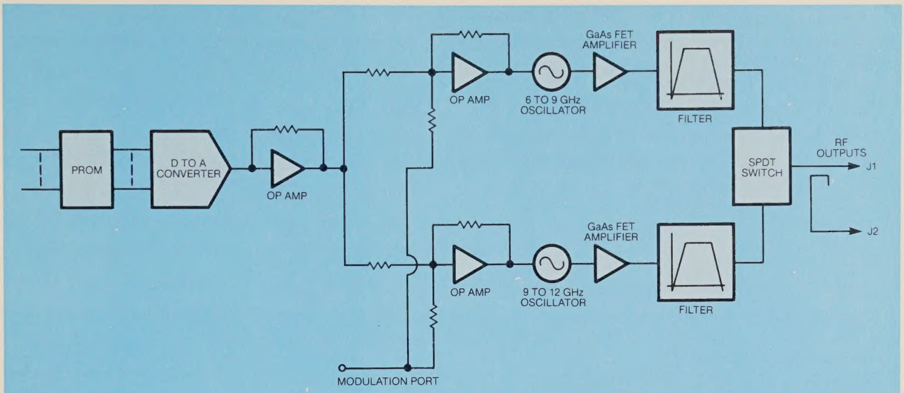


Figure 10. DTO for a jammer application.

oscillators covering the 6-to-12 GHz frequency range is shown in Figure 11, and the performance characteristics are summarized in Table II.

The primary purpose of a jammer is to put out the maximum amount of radiated energy over the desired frequency range. In other words, the power-spectral density must be maximized.

Several key specifications for the DTO affect system performance, especially as they relate to power spectral density, including frequency accuracy, modulation-sensitivity variation, and modulation bandwidth.

FREQUENCY ACCURACY

Frequency accuracy for a DTO is defined as the maximum deviation from the ideal frequency at a given digital input, including the effects of frequency change over temperature. The better the frequency accuracy of

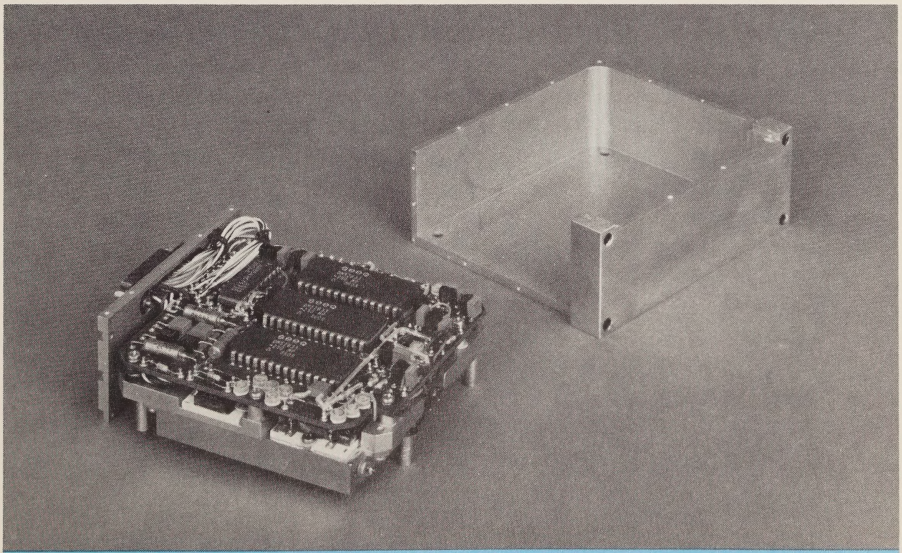


Figure 11. WJ-2855-37 6 to 12 GHz DTO.

RF Characteristics[1] [2]	Guaranteed
Frequency Range	6.0 to 12.0 GHz
Power Output, Minimum (J1 Port)	+7.5 dBm
Power Output Variation, Maximum (J1 Port)	4.5 dB
Power Output Variation, Maximum (J2 Port)	–20 to –10 dBm
Frequency Drift Over Temperature[3], Maximum	40 MHz
Spurious Output Suppression	
Harmonic (nf_0), Minimum	23 dB
Harmonic ($nf_0/2$)[4], Minimum	23 dB
In-band, Non-harmonic, Minimum	50 dB
Pushing Factor, Maximum	0.25 MHz/V
Pulling Figure (2.0:1 VSWR), Maximum	2 MHz
Pulling Figure (Infinite VSWR), Maximum	5 MHz
Tuning Characteristics	
Tuning Resolution	13-bit
Digital Tuning Range[6]	545 to 7946
Modulation Sensitivity Range, Maximum	100 MHz/V
Modulation Sensitivity Range, Minimum	60 MHz/V
Non-linearity[5], Maximum	±10 MHz
Post Tuning Drift (1.7 μsec to 1.0 msec), Maximum	5.0 MHz
Post Tuning Drift, 1.0 msec to 1 minute, Maximum	3.0 MHz
Modulation Bandwidth (400 MHz deviation)[9], Minimum	8 MHz
Nominal Step Size	1 MHz ±50%
Input Power Requirements	
Oscillator Bias[7]	+15 Volts @ 500 mA, Maximum –15 Volts @ 400 mA, Maximum +5.2 Volts @ 600 mA, Maximum –5.2 Volts @ 100 mA, Maximum
Heater Voltage[8]	115 Volts AC
Heater Current at Turn-on	1.5 Amps, Maximum
Heater Current, Steady-state at –54° C	1.5 Amps, Maximum
Environmental Specifications	
Operating Temperature[3]	–54°C to 85°C
Storage Temperature	–54°C to 125°C
Mechanical Specifications	
Package Dimensions Excluding Connectors and Mounting Flanges (LxWxH)	4.00 x 3.50 x 1.50 inches
Weight, Maximum	20 ounces
RF Output Connector	SMA Jack
Tuning Input Connector	Multi-pin connector (RFI Protected)
Bias and Heater Connections	Multi-pin connector (RFI Protected)
W-J Outline Drawing Number	337758

Notes:
1. The WJ-2855-37 is an rf oscillator employing varactors and bipolar transistors as the active elements. It also contains the following interface elements: isolation amplifier (active isolator), voltage regulator, proportionally controlled internal heater, D/A converter, PROM, and rf switch.
2. Unless otherwise noted, performance is specified for operation into a nominal matched load (VSWR ≤1.2:1) at laboratory ambient temperature.
3. Temperature is measured on the oscillator mounting surface.
4. The output of the WJ-2855-37 is taken from the second harmonic of the oscillation frequency, creating harmonically related ($nf_0/2$) spurious responses.
5. The tuning non-linearity is the maximum deviation from linear tuning between the specified tuning voltage extremes and includes the effect of frequency drift over the operating temperature range.
6. The tuning voltage range specifies the maximum voltage range required to tune from minimum to maximum frequency.
7. Protective circuitry guards against damage due to overvoltage (up to 10 percent) and transient reverse voltages.
8. The heater is a self-regulating, proportionally controlled unit, isolated from bias and signal grounds.
9. With the VCO tuning port modulated sinusoidally by a 50-ohm source, the modulation bandwidth is defined as that modulation frequency at which the frequency deviation decreases to 0.707 of its low frequency value.

Table II. WJ-2855-37 digitally tuned oscillator.

the DTO, the higher power density that can be achieved, because it is not necessary to modulate the oscillator over as broad a frequency range to ensure that the signal to be jammed is covered. Using PROMs at the digital input to the DTO, accuracies of ±10 MHz can be achieved over the -54° to +85° centigrade range. Other techniques may be used to achieve better accuracies, including the use of synthesizer techniques and calibration routines.

MODULATION SENSITIVITY

The power spectral density is also affected by the variation in modulation sensitivity at the modulation port, as measured in MHz/V. Given a constant amplitude modultion signal, if the modulation port is connected directly to the varactor, as shown in Figure 10, the deviation of the modulated signal and, therefore, the power density, will vary directly with the variation in modulation sensitivity of the oscillator itself. This variation is shown in Figure 12. As the output frequency of the oscillator increases, the modulation sensitivity decreases. Therefore, for a constant modulation signal, the deviation decreases and the power spectral density over the deviated spectrum increases. This effect is undesirable in transmitter applications and, therefore, designs have been developed to correct it.

The most straightforward technique is to place a linearizer circuit between the oscillator and modulation circuit, as shown in Figure 13. This reduces the variation in modulation sensitivity across the band, thereby making the power density and deviation more constant. Overall variations of less than ±15% can be achieved using this technique. The disadvantage of the technique is that circuits having bandwidths greater than 10 MHz are very difficult to achieve.

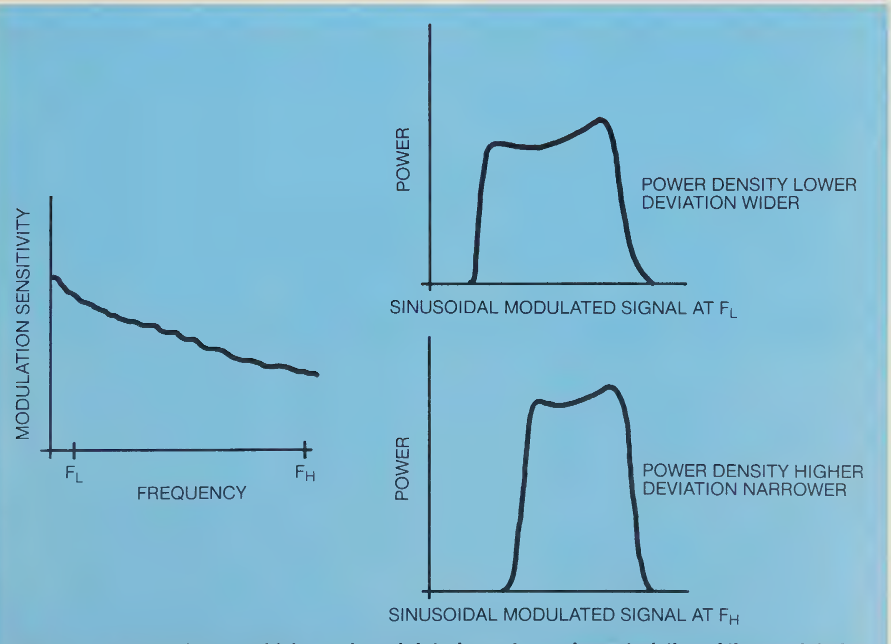


Figure 12. Modulation sensitivity and modulated spectrum characteristics of the modulation port of a DTO.

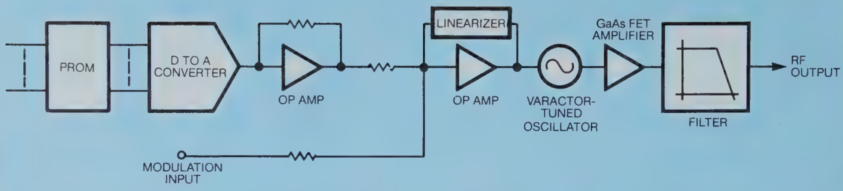


Figure 13. DTO for jammer application with linearizer to reduce variation in modulation sensitivity.

To achieve higher modulation bandwidths, another technique has been developed which uses a variable-gain amplifier, as shown in Figure 14. The gain of the amplifier is controlled by a PROM and D-to-A converter as the unit is tuned across the operating frequency range. Using this technique, the variation in modulation sensitivity and, therefore, variation in power density and deviation are less than ±5%. However, this technique has one basic problem. The gain of the amplifier is set at one frequency, so when modulating the oscillator over frequencies for which the modulation sensitivity of the oscillator itself varies, the power density and deviation will vary. This is especially evident when the deviations become wide, e.g. 100 to 500 MHz. In addition, a fast change in the modulation sensitivity of the oscillator will show up in the modulated spectrum, as illustrated in Figure 15. By controlling the overall variation in modulation sensitivity of the oscillator and aligning out any fine-grain variations, this technique has proven to be superior to the linearizer technique.

One other effect to be considered is *centroid shift*. Due to the nonlinear characteristics of the modulation sensitivity, the center of the modulated spectrum shifts, compared to the location of the unmodulated carrier. The shift necessitates that the system be designed to have slightly larger deviation to cover all threat frequencies. This also results in lower power density than if the modulation sensitivity were constant, as illustrated in Figure 16. This shift can be minimized by aligning the rf oscillator with minimum modulation sensitivity variation. The effect can be virtually eliminated if deviation information can be input to the variable gain amp PROM.

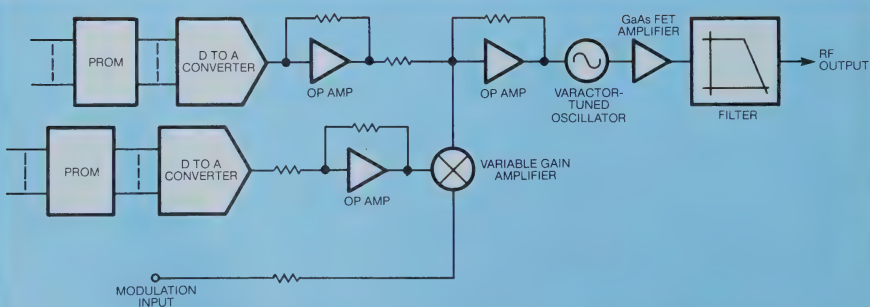


Figure 14. DTO for jammer application with a digitally controlled variable-gain amplifier to reduce variation in modulation sensitivity.

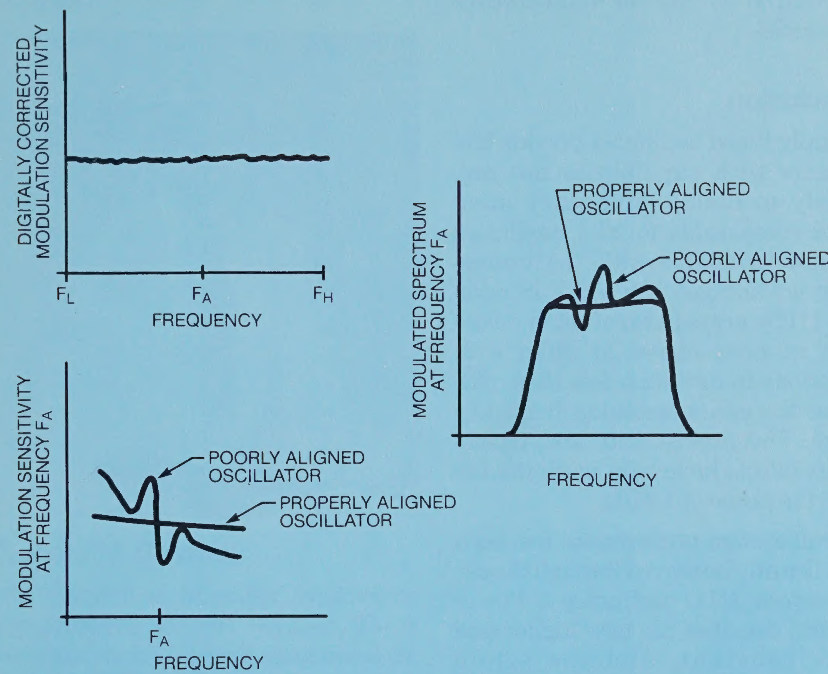


Figure 15. Modulation characteristics of digitally corrected modulation port of a DTO.

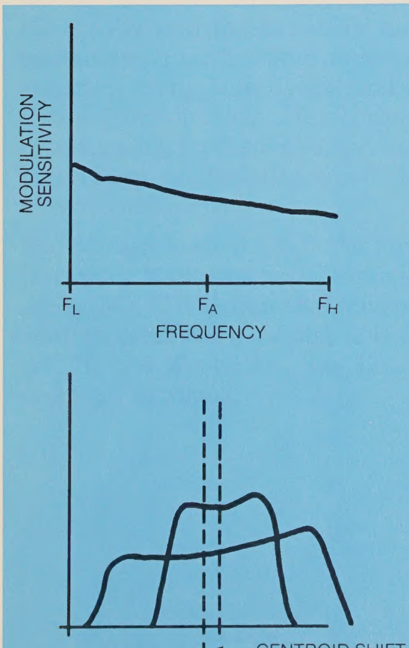


Figure 16. Centroid shift.

MODULATION BANDWIDTH

The modulation bandwidth of a modulation port is defined as that modulation frequency at which the frequency deviation changes by $\pm$(x)dB from its low-frequency values. Typically, (x) is specified in the range of 1 to 3 dB.

To achieve a certain power spectral density, it is necessary to modulate the oscillator over a broader deviation at low modulation frequencies to ensure the frequencies to be jammed are covered at higher modulation frequencies if the bandwidth decreases. This means that the overall power spectral density will be lower than if the modulation bandwidth were flatter.

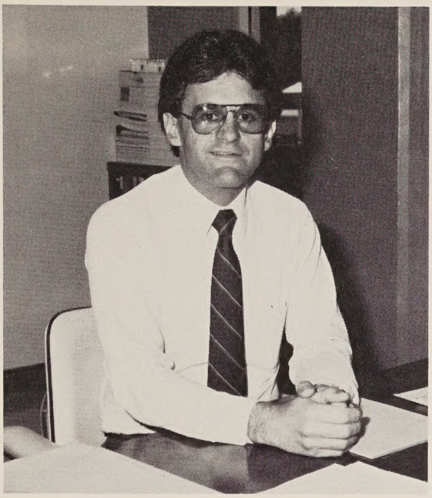
The modulation bandwidth also varies as a function of the DTO operating frequency. This, too, affects the power spectral density as the unit is tuned across the operation frequency range, especially at higher modulating frequencies.

Conclusion

Digitally tuned oscillators provide EW systems with capabilities not previously available. Frequency accuracies comparable to YIG oscillators are now available with the tuning-speed advantages of a VCO. In addition, DTOs are capable of being modulated at rates above 20 MHz, with variations in deviation less then ±5% across the entire operating frequency range. Post-tuning drift and repeatability effects have been minimized to be in the range of 1 MHz.

Overall system performance has been significantly improved through the use of modern DTO technology. Power spectral densities are now higher and more constant, and the set-on accuracies have been enhanced.

Author:



Ronald N. Buswell

Mr. Buswell is Manager, Solid-State Department, Stewart Division. He is responsible for all solid-state research, development, and production activities at the Stewart Division. This includes the development and production of electrically and mechanically tuned oscillators across the entire microwave spectrum, using both hybrid and discrete circuit technology. He is currently concentrating on the development and production of digitally tuned and phase-locked oscillators.

Mr. Buswell holds a B.S.E. (EE) from Michigan Technological University and an M.S.E. (EE) from the University of Michigan. He is a member of IEEE, GMTT, Eta Kappa Nu, Tau Beta Pi and Phi Eta Sigma.

WATKINS-JOHNSON COMPANY
3333 HILLVIEW AVENUE
PALO ALTO, CA 94304-1204
(415) 493-4141

ADDRESS CORRECTION REQUESTED

BULK RATE
U.S. POSTAGE
PAID
PERMIT NUMBER
173
MILPITAS
CALIFORNIA

WATKINS-JOHNSON

Facility Locations

United States

CALIFORNIA

Watkins-Johnson
3333 Hillview Avenue
Palo Alto, 94304-1204
Telephone: (415) 493-4141

Watkins-Johnson
2525 North First Street
San Jose, 95131-1097
Telephone: (408) 435-1400

Watkins-Johnson
440 Kings Village Road
Scotts Valley, 95066-4081
Telephone: (408) 438-2100

MARYLAND

Watkins-Johnson
700 Quince Orchard Road
Gaithersburg, 20878-1794
Telephone: (301) 948-7550

Watkins-Johnson
8530 Corridor Road
Savage, 20763
Telephone: (301) 497-3900

NORTH CAROLINA

Watkins-Johnson
100 West Powell Road
Fuquay-Varina, 27526-9399
Telephone: (919) 552-6161

International

UNITED KINGDOM

Watkins-Johnson
Dedworth Road
Oakley Green
Windsor, Berkshire SL4 4LH
Telephone: (0753) 869241
Telex: 847578
Cable: WJUKW-WINDSOR

ITALY

Watkins-Johnson S.p.A.
Piazza G. Marconi 25
00144 Roma-EUR
Telephone: 592 45 54
591 25 15
Telex: 612278
Cable: WJ ROM I

The Watkins-Johnson *Tech-notes* is a bi-monthly periodical circulated to educational institutions, engineers, managers of companies or government agencies, and technicians. Individuals may receive issues of *Tech-notes* by sending their subscription request on company letterhead, stating position and nature of business to the Editor, *Tech-notes,* at Watkins-Johnson's Palo Alto, California address. Permission to reprint articles may also be obtained by writing the Editor.

 Printed in U.S.A.