403 MHz SAW OSCILLATOR

C. J. Dodson
TRW Inc.
One Space Park
Redondo Beach, CA 90278

November 1981

Final Report

Approved for Public Release;
Distribution Unlimited

Prepared for:
ELECTRONICS TECHNOLOGY & DEVICES LABORATORY

ERADCOM
ARMY ELECTRONICS RESEARCH AND DEVELOPMENT COMMAND
FORT MONMOUTH, NEW JERSEY 07703
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circuit functions in a low-cost printed circuit approach rather than utilize high-cost commercially available components, since the oscillator is intended for use in an expendable application.
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1. SUMMARY

The objective of this program is the development of a 403 MHz surface acoustic wave oscillator suitable for use in an expendable radiosonde. Due to the extreme temperature range (-70°C to +70°C) the radiosonde must operate in, and the simultaneous deployment of many radiosondes operating within a limited bandwidth, temperature stability is the oscillator's most critical performance parameter. Stability of 200 ppm or better is required. The circuit is also required to tune from 400 MHz to 406 MHz, transmit 200 mW (+23 dBm), and be capable of both amplitude and frequency modulation. Specified performance is outlined in Table 1-1.

Table 1-1. Oscillator Performance Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Comment</th>
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<tr>
<td>Frequency</td>
<td>400-406 MHz</td>
<td>Settable to 50 ppm</td>
</tr>
<tr>
<td>Stability</td>
<td>200 ppm</td>
<td>-70°C to +70°C</td>
</tr>
<tr>
<td>Modulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAM</td>
<td>0 to 2000 pps</td>
<td></td>
</tr>
<tr>
<td>FM</td>
<td>100 KHz modulation</td>
<td>300 KHz/V Modulation Frequency</td>
</tr>
<tr>
<td>Output Power</td>
<td>200 mW</td>
<td>50 ohm load</td>
</tr>
<tr>
<td>Frequency Pulling</td>
<td>≤ ±20 ppm</td>
<td>$Z_L = 25$ to 75 ohms</td>
</tr>
<tr>
<td>Power Supply</td>
<td>24V ±10% &lt;2.5 watts</td>
<td>Other supply voltages can be considered</td>
</tr>
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During the first six months of the program the oscillator design was completed, and all the individual RF subcircuits were designed, fabricated, and tested. These circuits include the SAW delay line, loop amplifier, phase shifter, and an injection locked oscillator (ILO). During the second 6 months of the program, the individual oscillator circuits were integrated to form the radiosonde oscillator, and the oscillator was temperature compensated and tested.
This report discusses the overall oscillator design, gives a brief description of the design and performance of the various subcircuits of the oscillator, and a detailed description of the integrated oscillator's design and performance. The oscillator design is described in Section 2, design and performance of the individual subcircuits are described in Section 3, and the integrated oscillator design and performance is described in Section 4.

2. OSCILLATOR DESIGN

For a general description of the radiosonde oscillator design considerations, refer to the First Interim Report dated March, 1981.

A block diagram of the 403 MHz SAW Stabilized Oscillator is shown in Figure 2-1. The circuit consists of a relatively low power, tunable SAW oscillator driving an injection locked oscillator, plus associated DC circuitry. The SAW oscillator produces approximately 20 mW (+13 dBm) RF power, tunable from 400 MHz to 406 MHz. Both mechanical tuning for frequency selection and electronic tuning for frequency modulation are employed. The injection locked oscillator which is locked to the SAW oscillator output produces an RF output in excess of 200 mW (+23 dBm). The ILO therefore provides approximately 10 dB of gain. Bias switching circuitry in the ILO is used for pulse amplitude modulation (PAM). The DC circuitry consists of a voltage regulator to minimize frequency pushing, tuning and frequency modulation circuitry, and a temperature compensation network to compensate primarily for varactor reactance changes.
Specifications for the individual oscillator subcircuits were generated, and are summarized in Table 2-1. As these specifications imply, a 12V supply will be used throughout as opposed to the 24V currently used. All of the transistor circuitry performs optimally with 12V or less. Only the varactors in the phase shifter would benefit from using the full 24V available and due to the non-linear varactor C-V relationship, this benefit is small. The 12V supply was therefore chosen to conserve power.
<table>
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<th>Circuit</th>
<th>Parameter</th>
<th>Specified Performance</th>
<th>Comments</th>
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<tr>
<td>Delay Line</td>
<td>Center Frequency</td>
<td>403 ±0.150 MHz</td>
<td>ST-cut quartz</td>
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<td></td>
<td>3 dB Bandwidth</td>
<td>6.3 MHz</td>
<td></td>
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<tr>
<td></td>
<td>Loss (Matched)</td>
<td>≤ 20 dB</td>
<td></td>
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<tr>
<td></td>
<td>Delay</td>
<td>≤ 100 ns</td>
<td></td>
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<tr>
<td>Loop Amp</td>
<td>Frequency Band</td>
<td>&gt;350-450 MHz</td>
<td></td>
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<tr>
<td></td>
<td>Gain</td>
<td>≥ 40 dB</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PSAT</td>
<td>≥ 16.5 dBm</td>
<td></td>
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<tr>
<td></td>
<td>VSWR (In,Out)</td>
<td>≤ 2.5:1</td>
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<td></td>
<td>Vsupply</td>
<td>9V</td>
<td>Regulated</td>
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<td>Phase Shifter</td>
<td>Loss</td>
<td>&lt; 3 dB</td>
<td>Two cascaded phase shifters to be used</td>
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<td></td>
<td>Phase Shift</td>
<td>&gt;180°</td>
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<td>Loss</td>
<td>&lt;0.5 dB</td>
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<td></td>
<td>Power Out</td>
<td>≥ +23 dBm</td>
<td>200 mW</td>
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<td>Injection Locking Bandwidth</td>
<td>≥ +16 MHz</td>
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<td></td>
<td>PINj</td>
<td>+13 dBm</td>
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</tr>
<tr>
<td></td>
<td>Vsupply</td>
<td>12V</td>
<td>Unregulated</td>
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A review of Table 2-1 points out key features of the design. The loop amplifier gain of 40 dB exceeds the 30 dB loop loss by 10 dB. This is adequate to drive the amplifier well into saturation and provides margin for SAW and phase shifter variations. The delay in the SAW implies a mode spacing of 10.0 MHz. If 20 ns of delay in other components in the loop is assumed the mode spacing would be reduced to 8.3 MHz. This is well in excess of the 7 MHz 3 dB bandwidth of the SAW. Two phase shifters will be used in cascade. A
single phase shifter will generally produce no more than 250° phase shift. Therefore, two are required to produce a 360° phase shift. The ILO will lock over a range far in excess of the 6 MHz operating band. This is to account primarily for the drift in ILO natural frequency with temperature.

3. CIRCUIT DESIGN AND PERFORMANCE

Refer to the First Interim Report, dated March 1981, for a detailed description of the design and performance of the various oscillator circuits.

a. 403 MHz SAW Delay Line

It is required that the 403 MHz SAW oscillator be operated with one stable single mode output and be tunable over the 400 MHz to 406 MHz frequency range. To achieve this, the specifications for the SAW delay line were set as follows:

- Center Frequency: 403.0 ±0.15 MHz
- 3 dB Bandwidth: 6.3 ±0.1 MHz
- Time Delay: 0.10 ±0.01 μsec
- Insertion Loss (matched): <20 dB
- Substrate: ST Quartz
- Temperature Stability
  - Turnover Temperature ($T_0$): $-10^\circ C < T_0 < 10^\circ C$
  - 2nd Order Temperature Coefficient: $-3.2 \times 10^{-8}/(^\circ C)^2$

To meet these specifications, the delay line was designed to consist of one long and one short transducer, closely spaced one next to the other. The 3 dB bandwidth is largely defined by the long transducer. The transducers are both designed to operate at the fundamental frequency and contain split fingers to minimize reflection among fingers. The center-to-center separation between transducers is $40.3 \lambda_0$, where $\lambda_0$ is the acoustic wavelength.

Other design parameters are shown in the following table:
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<td>Number of Finger Parls</td>
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</tr>
<tr>
<td>Acoustic Aperture</td>
<td>$45 \lambda_0$</td>
</tr>
<tr>
<td>Finger Width</td>
<td>1.3 $\mu$m</td>
</tr>
</tbody>
</table>

The unmatched insertion loss of such a device should be approximately 40 dB. Upon matching, it can be reduced to 18 dB or less.

The schematic of the SAW delay line is shown in Figure 3-1. A ground bar has been placed between the transducers to cut down the direct electrical feedthrough.

Figure 3-1. SCHEMATIC OF 403 MHz SAW DELAY LINE
Performance of the unmatched delay line is shown in Figures 3-2 through 3-4. Matching networks for the SAW have been designed, built, and tested. A schematic of the matched circuit is shown in Figure 3-5. Performance of the matched delay line is shown in Figures 3-6 and 3-7.

b. Loop Amplifier

The loop amplifier is used to provide gain to overcome losses in all other loop elements. A schematic of the amplifier used for the SAW oscillator is shown in Figure 3-8. The circuit is a three-stage, lumped element design using two BFR 91 transistors and one MRF 559. The MRF 559 is used in the amplifier output stage to provide saturated output power in excess of 40 mW (+16 dBm). A lumped element design was used to minimize circuit size. Distributed matching networks would have required more volume than available.

Test results for the amplifier are shown in Figures 3-9 through 3-13. Figure 3-9 shows linear gain in excess of 40 dB for temperatures ranging from -70°C to +70°C. Saturation characteristics for the circuit are shown in Figures 3-10. Saturated gain for input power of +18 dBm is shown in Figure 3-11. Transmission phase through the amplifier for linear and saturated operating conditions is shown in Figures 3-12 and 3-13, respectively.

c. Phase Shifter

The phase shifter block diagram is shown in Figure 3-14. The circuit consists of a hybrid coupler loaded with tunable, reflective loads. In this design, power incident at port 1 is split with equal amplitude, and 90° relative phase between ports 2 and 3. Since the loads at ports 2 and
Figure 3-2. 403 MHz SAW Unmatched Passband and Phase
Figure 3-4. 403 MHz SAW Unmatched Reflection Coefficients
Figure 3-6. 403 MHz SAW Matched Passband and Phase
Figure 3-7. 403 MHz SAW Matched Reflection Coefficients
L1 = L3 = 5 turns #30 wire on #60 drill.
L2 = L4 = 6 turns #30 wire on #60 drill.
L5 = 3 turns #30 wire on #60 drill.
L6 = 11 turns #30 wire on #60 drill.
RF CH = 0.5 μH inductor.

Figure 3-8. 403 MHz SAM AMP
3 are reactive, the power incident on these loads from ports 2 and 3 is reflected back into the coupler. The reflected signals experience a phase shift associated with the reflection coefficient of the loads, and since the loads are tunable this phase shift can be varied. The reflected signals entering the coupler at ports 2 and 3 add in phase at port 4 and add out of phase (cancel) at port 1. Therefore, this circuit will transfer a signal incident at port 1 to port 4 with a phase shift which is a function of the angle of the reflection coefficient of the loads.

The design of the hybrid coupler itself can be either distributed or lumped. For this application a lumped element design was chosen to minimize size. A schematic of this coupler is shown in Figure 3-15, where

\[ L = 19.7 \, \text{nH} \]
\[ C = 7.9 \, \text{pF} \]
The design of the circuit which loads the hybrid coupler is shown in Figure 3-16. This load consists of a shunt inductance, a varactor, and a DC blocking capacitor. The reflection coefficient of the load is

\[ \rho = \frac{Z_L - Z_0}{Z_L + Z_0} \]

where

\[ Z_L = \text{load impedance} \]
\[ \frac{Z_{\text{ind}}Z_{\text{cap}}}{Z_{\text{ind}} + Z_{\text{cap}}} \]

\[ Z_0 = \text{system characteristic impedance (50 ohms typical)} \]
Test results for two cascaded phase shifters (consisting of 2 couplers and 4 loads) are shown in Figure 3-17. This figure is a plot of both loss and phase through the circuit as a function of tuning voltage. The data shows loss varying from approximately 5 dB at 0.5V down to 2 dB at 10V. The decreasing loss results from a decrease in diode series resistance with increasing reverse bias. The data also shows phase varying from 18° at 0.5V to +180° at just below 2V, to -36° at 5V and back to +18° at 10V. A full 360° shift has been realized with this cascade of two phase shifters.

One of the difficulties encountered when using varactor diodes is their capacitance variation with temperature. This variation translates into a change in reflection coefficient and therefore a change in phase through the circuit. The frequency of the oscillator therefore will drift with temperature. Tests have been run on the dual phase shifter to characterize temperature performance. The detailed results are summarized with the graph in Figure 3-18. It is the frequency drift with temperature caused by varactor changes which requires that a temperature compensation network be used. The compensating voltage is summed with the tuning and modulation voltages applied to the varactor.

d. **Injection Locked Oscillator**

The injection locked oscillator (ILO) is used to amplify the output of the SAW oscillator to the required 200 mW (+23 dBm). Pulse amplitude modulation is also accomplished in the ILO. A schematic of the circuit is shown in Figure 3-19. The oscillator is of the form of a Colpitts with a resonant tank in the collector circuit and feedback to the emitter. The injection locking signal is applied to the emitter-base junction.
Figure 3-17. 403 MHz BREADBOARD DOUBLE PHASE SHIFTER
Figure 3-18. PHASE SHIFTER TUNING CHARACTERISTICS
L2 = 10 turns #30 wire on #72 drill (25 mils diameter)
R* = SIT resistor for bias (~100 mA), 1K-5K ohms.
L1 = printed inductor.

Figure 3-19. 403 MHz ILO
Test results for the oscillator are shown in Figures 3-20 through 3-22. Figure 3-20 is a plot of injection locking bandwidth vs injection locking power. Figure 3-21 shows injection locking bandwidth vs temperature. Output power vs frequency is shown in Figure 3-22.
Figure 3-21. INJECTION LOCKING BANDWIDTH vs TEMPERATURE
4.0 INTEGRATED OSCILLATOR

A photograph of the integrated oscillator circuitry is shown in Figure 4-1. The oscillator package is shown in Figure 4-2. This package is identical to that currently used and was provided by VIZ Manufacturing Co., Philadelphia, PA. Test results for the integrated oscillator are shown in Figures 4-3 through 4-10, and in Table 4-1. Figures 4-3 and 4-4 show the tuning range and output power of the two delivered oscillators. Output power was greater than +23 dBm for both circuits over the complete tuning range. Tuning range for both oscillators exceeded the required 400-406 MHz. Settability is shown in Table 1. Settability, here, is a measure of how accurately frequency can be set within a few seconds. As the table indicates, an error of approximately 20 ppm can be expected in tuning the circuits. Intermittent operating characteristics are shown in Figures 4-5 and 4-6. For this test, the oscillator's were stabilized at an initial frequency (403.007 and 403.036 MHz), turned off for 3 minutes, then turned back on. Frequency after turn-on was observed for a minimum of 5 minutes. The curves indicate frequency differences on the order of 5 ppm can be expected with intermittent operation. Figures 4-7 and 4-8 show frequency pushing characteristics of the oscillators. The curves show frequency pushing of 0.0035 MHz/V and 0.0275 MHz/V for +1V around nominal bias. Temperature stability of the oscillator is plotted in Figures 4-9 and 4-10. Stability for Oscillator #1 was 200 ppm. Stability for Oscillator #2 was 305 ppm for the limited temperature range of +50°C. For the +70°C range, stability was 814 ppm. This relatively poor temperature performance results almost totally from the temperature characteristics of the tuning varactors.
Figure 4-2. OSCILLATOR PACKAGE
Table 4-1. SETTABILITY

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<th>Desired Frequency (MHz)</th>
<th>Tuned Frequency</th>
<th>Error (ppm)</th>
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<tr>
<td>406.00</td>
<td>406.016</td>
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Average Error = 19.66 ppm
Figure 4.10. TEMPERATURE STABILITY, OSCILLATOR 42
5.0 CONCLUSION

This program has demonstrated the feasibility of incorporating SAW devices in radiosonde oscillator applications. It has also revealed a fundamental problem in the design approach used here and/or in the oscillator specifications. The requirements for temperature stability, wide tuning range, continuous tuning, frequency modulation, and low cost conflict with each other. The requirement for low cost dictates the use of uncomplex circuitry, which requires little or no tuning, and uses the minimum number of components. For the design described in this report, the cost requirement led to the use of a single delay line. The wide tuning range required that a SAW of relatively short delay be used, thereby effectively minimizing the stabilizing effect of the delay line. The frequency modulation requirement dictated the use of an electronically controlled phase shifter. For this design the varactor tuned phase shifter was used for both tuning and modulation - again to help minimize cost.

The resulting oscillator lacked the temperature stability inherent in ST-cut quartz. The temperature instabilities of the varactors dominated the oscillator stability and required the use of temperature compensation. This performance suggests a modified design be investigated during the advanced development of this circuit. The development of a different phase shifter is indicated. It is recommended that a mechanical phase shifter be used for tuning while a lightly coupled electronic phase shifter be used for modulation. By lightly coupling the electronic phase shifter and
requiring it to produce only a few degrees instead of 360°, stability can be improved by a factor of ~100. The mechanical phase shifter should provide the full 360° phase shift. Development of a mechanical phase shifter will not be trivial. The requirements for stability, continuous tuning, small volume, and low cost complicate the design; but this approach will allow the SAW to dominate the temperature drift of other oscillator circuits.
APPENDIX A

SAW PERFORMANCE vs TEMPERATURE MEASUREMENTS
MATCHED SAW PASSBAND VARIATION WITH TEMPERATURE

![Graph showing the variation of loss (dB) with frequency (MHz) for different temperatures. The graph includes curves for temperatures of -70°C, -25°C, 0°C, +25°C, +50°C, and +70°C. The x-axis represents frequency in MHz, with values ranging from 391 to 415 MHz. The y-axis represents loss in dB, with values ranging from -50 dB to -18 dB.](image-url)
APPENDIX B

AMPLIFIER PERFORMANCE

vs

SUPPLY VOLTAGE AND TEMPERATURE
463 MHz SAW REF Vcc=11V Pin=-18dBm

PHASE (Deg.)

-50°C -25°C 0°C +25°C +50°C

-70°C -30°C +30°C +70°C
403 MHz SAW AMP $V_{cc}=13V$ $Pin=-40$dBm
APPENDIX C

PHASE SHIFTER CHARACTERISTICS
403 MHz DUAL PHASE SHIFTER

- $0^\circ C$
- $-25^\circ C$
- $-50^\circ C$
- $-70^\circ C$

PHASE (Deg.)

381, 387, 403, 425 MHz
4033 MHz DUAL PHASE SHIFTER $V_t=1.0\text{V}$
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