AN AM BROADCAST BAND RECEIVER
WITH DIGITALLY SYNTHESIZED TUNING

by

Lee Gage Stanley

Submitted in Partial Fulfillment
of the Requirements for the
Degree of Bachelor of Science
at the
Massachusetts Institute of Technology

January 1978

Signature of Author.................................................................

Department of Electrical Engineering, January 1978

Certified by.................................................................

Thesis Supervisor

Accepted by.................................................................

Chairman, Departmental Committee on Theses

ARCHIVES

APR 19 1978
AN AM BROADCAST BAND RECEIVER
WITH DIGITALLY SYNTHESIZED TUNING

by

Lee Gage Stanley

ABSTRACT

This thesis describes the design, construction, and evaluation of an
AM receiver utilizing electronic tuning. It includes an investigation
into some of the issues raised by this tuning method and the author's
suggestions for further refinements.

Thesis Supervisor: James K. Roberge

Title: Professor of Electrical Engineering
CONTENTS

ABSTRACT. .................................................. 2
LIST OF FIGURES ............................................ 4
LIST OF GRAPHS. ............................................. 5
ABBREVIATIONS .............................................. 6
INTRODUCTION. ............................................... 7

CIRCUIT DESCRIPTIONS
  Keyboard and Keyboard Buffer .......................... 8
  Programmable Frequency Divider; Reference Oscillator ..... 9
  Phase-Frequency Detector; Loop Amplifier ................ 10
  Antenna Circuit, RF Amplifier ........................... 10
  Local Oscillator .......................................... 12
  Mixer ..................................................... 13
  IF Amplifier - AGC Circuit .............................. 14

ALIGNMENT AND TRACKING .................................. 14
SPECIFICATIONS ............................................. 40
REFERENCES .................................................. 41
LIST OF FIGURES

Figure 1  Block Diagram. ................................. .18
Figure 2  Keyboard and BCD Encoding Circuitry. ....... .19
Figure 3  Key Debouncing Circuitry; Keyboard Buffers .... .20
Figure 4  Programmable Divider; Reference Oscillator .. .21
Figure 5  Phase-Frequency Detector; Loop Amplifier ..... .22
Figure 6  Bandswitch and Gainswitch. .................... .23
Figure 7  Antenna Circuit. ............................... .24
Figure 8  Local Oscillator ............................... .25
Figure 9  IF Amplifier; AGC Circuit. .................... .26
Parts List. ............................................. .27
LIST OF GRAPHS

Graph 1A (l.o./r.f.) vs r.f. ......................... 35
Graph 1B (l.o./r.f.) vs r.f. ......................... 35
Graph 2 \((.7 + aV)^{1/2}\) vs \(V\) ......................... 36
Graph 3 \((.7 + aV)^{-1/2}\) vs voltage (V) for \(a = .5, .75, 1.33\) ........ 37
Graph 4 \([( .7 + V)/(.7 + aV)\]^{1/2} vs V for \(a = .5, .75, 1.33\) .... 38
Graph 5 \((.7 + V)^{1/2}\) vs \(V\) ......................... 39
ABBREVIATIONS

AGC - Automatic Gain Control
AM - Amplitude Modulation
BCD - Binary Coded Decimal
C - Capacitor or Capacitance
DC - Direct Current
FM - Frequency Modulation
I - Inductor or Inductance
IC - Integrated Circuit
IF - Intermediate Frequency
kHz - Kilohertz
MOSFET - Metal Oxide Semiconductor Field Effect Transistor
R - Resistor or Resistance
RF - Radio Frequency
T - Transformer
V - Voltage
INTRODUCTION -- OVERVIEW AND APPROACH

The commercial AM Broadcast band extends from 535 to 1605 kHz and is divided into 107 channels (540 to 1600 kHz inclusive) with 10 kHz separation between assignable frequencies. Because these carrier frequencies are discrete and uniformly spaced, digital circuitry is naturally suited to controlling the channel selection process. The block diagram (Figure 1) illustrates that this receiver comprises a digital control section interfaced to a superheterodyne tuner of standard design format.

Specifically, since all assignable frequencies end in 0, three digits at most are needed to uniquely specify any station (2 digits from 540 to 990 kHz, 3 digits from 1000 to 1600 kHz). Central to this receiver's operation, then, is the synthesis of its local oscillator signal from such a 3 digit number and a crystal controlled reference oscillator, using phase-lock techniques. With this tuning method, a station is selected by keying in its operating frequency, which then appears on the display. The digital circuitry interprets this number, producing control signals which permit the correct tuning and tracking of the receiver's rf sections.

The circuit descriptions and tracking discussion describe these processes in detail.
CIRCUIT DESCRIPTIONS

Keyboard and Keyboard Buffer (see Figures 2 and 3)

When any 0-9 key is depressed, integrated circuits 1, 2, and 3A (IC's 1, 2, and 3A) convert the entry into its BCD equivalent. A monostable multivibrator, IC4, with IC5 and capacitor C1, form a debouncing circuit to prevent multiple entries from a single keystroke. Shift register IC8 keeps track of which station frequency digit is being entered and so multiplexes that digit to the appropriate buffer register, IC's 9-12.

A station's frequency is entered as follows: First the Clear Entry (CE) key is depressed which sets the outputs of IC's 8-12 to zero. The steering logic consisting of IC6 B, C, D and IC7 B and C causes the S1 input of IC8 to go high and enables a parallel load at inputs QA and QB. If the first keyboard digit entered is a "1", a 3-digit station frequency is implied. Accordingly, line A1 is high, A7 is low, and a "1" will appear at the QA output of IC8 when the clock next goes high. Since this QA output is connected to the clock input of IC9 a BCD "1" is entered into this buffer register. If, for example, the first digit is a seven, line A7 will go high and a "1" will first appear at the QB output of IC8. This pin is connected to the clock of IC10 and a BCD 7 will be entered into buffer IC10 first. In this manner a three-digit entry will be stored in IC's 9-11 and a two-digit entry in IC's 10-11. When all buffers are filled, IC 6A "locks out" the clock so that all further keyboard entries (except CE) are ignored.
NOTE: An extra buffer, IC12, has been included in this design to make it compatible for use in a digital FM receiver where 4 significant digits are required to specify some stations. The outputs of this register are not connected in the system under discussion.

Programmable Frequency Divider; Reference Oscillator (see Figure 4)

The outputs of the 4-section programmable divider and the crystal controlled reference oscillator are the signals which the phase detector circuitry (Figure 5) will compare. The frequency to be divided is the local oscillator, which is applied to the clock input of the lowest order counter, IC1. The programmable input to the divider is the BCD station frequency stored in the keyboard buffers. Since the local oscillator is 455 kHz above the station frequency, 455 BCD must be added to the 3-digit station code in order to produce a 1 kHz output across the entire spectrum. This addition is achieved by presetting input QB on the highest order counter (IC4) at the beginning of each count cycle. The number then entered into the divider is the station frequency + 2000. The 7410 and 7427 circuits (IC's 5 and 6) are connected to the outputs of the four counters such that a reload and output pulse is produced when the counters have clocked down to 1545 (BCD). The divisor so produced is 2000 - 1545 + station frequency = station frequency + 455 as desired. Since the local oscillator is operating X1000, the output is 1 kHz.
Phase-Frequency Detector; Loop Amplifier (see Figure 5)

When the two input signals are the same frequency, a DC voltage proportional to their phase difference is produced by the MC4044 circuit (IC1). Suitably amplified and filtered, this feedback voltage is applied to the tuning diodes in the local oscillator tank circuit, thus maintaining correct frequency and completing the phase locked loop.

As discussed in the next section, the required tuning voltage range is from +1.5 to +18 volts in each band segment. Because the usable voltage output of IC1 is approximately +1 to +4 volts, simple linear amplification cannot produce the required voltage swing. Piecewise linear amplification is employed with the necessity for switching amplifier gain within each band segment. Accordingly, the gain of IC2 is set to 3/2 when tuning stations from 540 to 690 and 940 to 1190 kHz. For frequencies 700-930 and 1200-1600 kHz, IC's 1C,1D,2C,2D,3A, and 3B (Figure 6) comprise a gainswitch which turns on transistor Q1 (Figure 5) and boosts the amplifier gain to approximately 5.

Antenna Circuit; RF Amplifier (see Figure 7)

The antenna and rf amplifier sections follow the design conventions of today's quality AM receivers. The rf amplifier is included to improve selectivity and sensitivity. The high input impedance of the MOSFET used in the gain stage minimizes loading of the antenna circuit. In addition, the square law transfer function of the MOSFET results in improved signal handling capability, including resistance to cross modulation, over that
of the bipolar transistor (see Mixer Section for further discussion). By applying a negative voltage to gate 2 of this amplifier, up to 85 dB of gain reduction can be achieved.

The tuned antenna and rf amplifier circuits must select signals from 540 kHz to 1600 kHz, a change of 300% over the broadcast spectrum. Since the frequency of a capacitively tuned circuit is proportional to \(1/C^2\), the capacitance ratio over the broadcast spectrum is \((\text{maximum frequency}/\text{minimum frequency})^2 = 9\). Tuning diodes with ratios of this magnitude are available (Motorola MV1400 series) but their present cost of approximately nine dollars was prohibitive considering that several different values may have been needed as the receiver design evolved.

Instead, a bandswitching circuit was designed which makes possible the use of the less costly Motorola MV100 and MV2100 diodes (about $1 each) whose capacitance ratios (maximum capacitance/minimum capacitance) are 5 and 3 respectively.

An MV109 diode tunes each circuit from 1600 kHz to 940 kHz. At 930 kHz and below, the bandswitch logic (see Figure 6), IC's 1A, 1B, 2A, 2B, and 4A turn on transistor Q1. This causes the 1N916 diodes in each tuned circuit to conduct, switching in the MV2100 tuning diodes. The combined diodes then tune the low-band from 930 to 540 kHz. 1N916 diodes are employed because their low junction capacitance (2 picofarads maximum at 0 voltage) effectively isolates the MV2100's from the circuit when Q1 is off. This design requires a tuning voltage range of from 1.5 to 18 volts for each band segment.
Two types of antenna coils are in common use today. The older version is a 240 microHenry ferrite rod designed to resonate with 365 picofarads of capacitance. The newer type is a 700 microHenry coil commonly used in transistor radios, and tuned with a smaller 130 picofarad variable capacitor. The second type is used in this design because the smaller tuning capacitance is compatible with the range available in the MV100 series diodes.

To simplify the tracking problem (see ALIGNMENT AND TRACKING), it is necessary that the inductance of the rf amplifier transformer T1 equal that of the antenna coil. No 700 microHenry rf transformer could be found, however. A slug tuned 455 kHz if transformer with internal capacitor removed, was found to be adjustable to 700 microHenries and was employed as T1.

Local Oscillator (see Figure 8)

The local oscillator coil is a J.W. Miller 2069 and the schematic shown is a modified version of the suggested circuit supplied with this coil. Variable resistors R1 and R3 are adjusted so as to provide nearly uniform oscillator amplitude over the spectrum and to provide sufficient signal amplitude at gate 2 of the mixer transistor for maximum conversion gain. The output of the oscillator is lightly coupled by C5 (2.2 picofarads) to transistors Q2 and Q3 which form a common-drain common-base pair. This configuration affords high input impedance and some voltage gain. Transistor Q4 provides impedance matching to IC1, a 7413 Schmitt
trigger. The output of the 7413 is the local oscillator signal suitably buffered and conditioned for driving the programmable divider.

Mixer (see Figure 8)

The dual-gate MOSFET Q5 is used principally for two reasons. First, the output current of a practical amplifier can be expressed as a power series about its DC operating point:

\[ I = I_\text{dc} + \alpha V_g + \beta V_g^2 / 2! + \gamma V_g^3 / 3! + \ldots \]

where \( I_\text{dc} \) = DC bias point
\( V_g \) = Input signal voltage at the gate
\( \alpha \) = First derivative of transfer function (transconductance)
\( \beta \) = Second derivative of transfer function
\( \gamma \) = Third derivative of transfer function

The second and higher order terms of the above expansion account for signal distortion. Specifically the \( \beta V_g^2 / 2! \) explains the sum and difference terms in a product mixer. Cross modulation, intermodulation, and modulation distortion are results of the third and higher order characteristics of the transfer function. Since the MOSFET has a square law characteristic, it functions well as a product mixer without the higher order distortion.

Secondly, the dual gate structure, with the rf signal applied to gate 1 and the local oscillator signal to gate 2, affords good isolation between the two signal sources. The output of the mixer transformer is applied to the if amplifier.
IF Amplifier; AGC Circuit (see Figure 9)

Three if amplifier configurations, each incorporating a single 455 kHz ceramic filter, were built and evaluated before the circuit of Figure 3 was decided upon. The stop-band attenuation (27 dB) of this filter, a muRata CFU455F2, is not sufficient to adequately reject the local oscillator signal at the low end of the band.

The circuit shown employs an additional stage of tuned amplification consisting of transistor Q3 and a π section band-pass filter made from two standard if transformers. The detector is the standard envelope-type utilizing germanium diodes and R-C filtering. Synchronous demodulation was also tried using a Signetics NE561 phase locked loop. This method offered no audible improvement (other than voltage gain) for the complexity involved.

The agc amplifier composed of Q6, Q7, and Q8 produces a negative control voltage proportional to the if signal magnitude. This voltage is applied to gate 2 of the rf amplifier in order to maintain a more constant input to the mixer stage.

ALIGNMENT AND TRACKING

The alignment procedure begins with a crude adjustment of the local oscillator (Figure 8). With the bandswitch off and a frequency counter attached to the 7413, +2 volts is applied to input D. R1, R3, the coil slug, and C7 are adjusted until oscillation at approximately 1400 kHz occurs. Then the voltage is increased to +16.5 and C7 and the slug are
adjusted until 2055 kHz is produced. This process is repeated until close values are obtained. It is then repeated for the low band with target frequencies of 1045 and 1350 kHz (approximately) using C8 as the adjustment. When no further improvement seems possible, the bandswitch and tuning voltage test points should be reconnected to the circuit. Station frequencies are then keyed in and the local oscillator frequency checked to see that the entire band can be tuned.

The need for a constant difference frequency between the antenna/rf and local oscillator sections is the origin of the tracking problem. Ideally, the antenna and rf amplifier are tuned to the same frequency which is 455 kHz below the local oscillator. The percentage deviation of the antenna/rf circuits from this ideal is the tracking error. In maintaining this frequency difference over the AM band, the local oscillator will change from 995 (540 + 455) to 2055 (1600 + 455) kHz, or by a factor of 2.06. The antenna/rf sections must change by a factor of 2.96 (1600/540).

Because the resonant frequency of a capacitively tuned circuit is proportional to $1/C^{1/2}$, the ratio of the tuning capacitances of these sections is a nonlinear function of frequency.

In conventional receivers using mechanically linked 3-section variable capacitors, the first two sections of the unit have the same capacitance over the entire tuning range. In order to assure tracking, the antenna coil and rf transformer are adjusted to the same value of inductance, and the fixed plus stray capacitances of these two sections are
equalized with trimmers. The plates of the local oscillator section are then shaped to provide the correct capacitance ratio over the band. Similarly, in this voltage tuned receiver, the rf transformer is adjusted to the same inductance as the rod antenna. Then, when the stray capacitances are equal and equivalent diodes are used to tune these sections, the same voltage may be applied to each to produce tracking. With these sections tracking together, it is necessary to find the relationship between their capacitance and that of the local oscillator. Graph 1A shows the ratio of the local oscillator to the rf frequency as a function of rf frequency \([(rf + 455)/rf] \) versus rf. Since the inductors are fixed in all sections, the actual ratio of capacitances \( C_{rf}/C_{lo} \) is proportional to \((rf + 455 \text{ kHz}/rf)^2 \) as graphed in 1B. This curve must be "fitted" by the circuitry if accurate tracking is to be achieved. Such a curve is suggested by an arrangement in which \( C_{lo} \) initially changes less rapidly than \( C_{rf} \), but ultimately changes at the same rate. A simple series capacitor in the tank circuit of the local oscillator will produce this kind of change (see Reference 3):

Local Oscillator Tank Circuit

\[
C_{lo} = \frac{C_f C(v)}{C_f + C(v)}
\]
RF Amplifier Tank Circuit

Now, \[ C_{tf}/C_{lo} = \frac{C(v_2)\{C_f + C(v)\}}{C_fC(v)} \]

The junction capacitance of a varactor diode is proportional to

\[ 1/(.7 + V)^{1/2} \] (see Reference 4)

Therefore:

\[ C_{tf}/C_{lo} = (.7 + V)^{1/2} \left[ \frac{1}{(.7 + V)^{1/2} + C_f}\right]/(.7 + aV)^{1/2} \]

where \( V_2 = aV_1 \) and \( a \) is a constant. The voltage dependent terms of this expression are shown in graphs 2-15 for 3 values of \( a \). The term \( 1/(.7+V)^{1/2} \) has a negative slope (Graph 3) as does the desired \( C_{tf}/C_{lo} \) curve (Graph 1B). The term \[ [(V + V)/(.7 + aV)]^{1/2} \] can have a positive or negative slope (Graph 4) and therefore adjusts the rate of change. The fixed capacitance \( C \) makes it possible to scale the two terms whose sum equals \( C_{tf}/C_{lo} \). By adjusting \( a \), \( C \), and the local oscillator slug, tracking can be achieved.

The system just described does work, but the adjustment procedure is time consuming and tedious. Although not investigated by this writer, another approach, with the intention of simplifying the tracking adjustment, might involve the synthesis of an additional "fine tuning" voltage. Such a signal could be applied to the front end sections so as to maximize an easily obtained indicator of tuning accuracy, such as the if voltage.
FIGURE 1 Block Diagram
Figure 5: Phase-Frequency Detector, Loop Amplifier
PARTS LIST

FIGURES 2 AND 3

Resistors

All 1.5K ohm

Capacitors

C1 - .0015 microfarad

Integrated Circuits

IC1,IC2 - 7420
IC3 - 7432
IC4 - 74121
IC5 - 7400
IC6 - 7402
IC7 - 7404
IC8-IC12 - 74194

Keyboard keys

Single pole, normally open, momentary type

FIGURE 4

Resistors

R1,R2 - 1800 ohm
Capacitors

C1 - .01 microfarad
C2 - 33 picofarad variable
C3 - 10 picofarad

Integrated Circuits

IC1-IC4 - 74192
IC5 - 7410
IC6 - 7427
IC7 - 7400
IC8-IC10 - 7490

FIGURE 5

Resistors

R1, R2, R8 - 4.7K ohm
R3 - 56K ohm
R4, R5 - 500K ohm, variable
R6 - 1 Megohm
R7 - 10K ohm, variable

Capacitors

C1 - .22 microfarad

Coils

L1 - 2.5 milliHenry RF choke
Transistors

Q1, Q2 - 2N2222

Integrated Circuits

IC1 - Motorola MC4044P
IC2 - National Semiconductor LM324

FIGURE 6

Resistors

R1 - 4.7K ohms
R2 - 3.3K ohms

Capacitors

C1 - .1 microfarad

Diodes

D1, D2 - General Purpose Silicon Diode

Transistors

Q1 - 2N2222

Integrated Circuits

IC1 - 7432
IC2, IC3 - 7408
IC4 - 7404
Resistors

R1, R2, R5 - 220K ohm
R3 - 150K ohm
R4 - 220 ohm

Capacitors

C1, C2, C5-C7 - .1 microfarad
C3 - 3 picofarad
C4 - .05 microfarad

Diodes

D1-D4 - 1N916

Tuning Diodes

TD1 - MV2112
TD2 - MV2104
TD3, TD6 - MV109
TD4 - MV2111
TD5 - MV2107

Coils

L1 - 700 microHenry standard ferrite rod antenna coil

T1 - 30K primary, 6K secondary--made from a 455 kHz IF transformer with internal capacitor removed and slug adjusted to provide 700 microHenries of inductance
Transistors

Q1 - 40673 MOSFET

FIGURE 8

Resistors

<table>
<thead>
<tr>
<th>R1,R9</th>
<th>100K ohm, variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2,R10</td>
<td>1.5K ohm</td>
</tr>
<tr>
<td>R3</td>
<td>1K ohm, variable</td>
</tr>
<tr>
<td>R4,R8,R13</td>
<td>150 ohm</td>
</tr>
<tr>
<td>R5</td>
<td>220K ohm</td>
</tr>
<tr>
<td>R6</td>
<td>1 Megohm</td>
</tr>
<tr>
<td>R7</td>
<td>330 ohm</td>
</tr>
<tr>
<td>R11</td>
<td>68K ohm</td>
</tr>
<tr>
<td>R12,R14</td>
<td>100K ohm</td>
</tr>
<tr>
<td>R15</td>
<td>220 ohm</td>
</tr>
</tbody>
</table>

Capacitors

<table>
<thead>
<tr>
<th>C1</th>
<th>.02 microfarad</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2</td>
<td>2.2 picofarad</td>
</tr>
<tr>
<td>C3,C4,C6</td>
<td>.1 microfarad</td>
</tr>
<tr>
<td>C5,C7,C10</td>
<td>150 picofarad</td>
</tr>
<tr>
<td>C8</td>
<td>33 picofarad, trimmer</td>
</tr>
<tr>
<td>C11</td>
<td>.05 microfarad</td>
</tr>
</tbody>
</table>
Coils

T1 - J.W. Miller 2069
T2 - Heath Co. part no. 50-340

Diodes

D1, D2 - 1N916

Tuning Diodes

TD1 - MV2110
TD2 - MV2108
TD3 - MV109

Transistors

Q1, Q3, Q4 - 2N2222
Q2 - 2N4416
Q5 - Motorola HEP F2007

Integrated Circuits

IC1 - 7413

FIGURE 9

Resistors

R1, R6, R11, R16, R17, R26 - 10K ohm
R2, R5, R10, R14 - 100K ohm
R3, R8, R12 - 330 ohm
R4, R7, R20 - 4.7K ohm
R9 - 2K ohm
<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R13</td>
<td>68K ohm</td>
</tr>
<tr>
<td>R15, R25</td>
<td>1K ohm</td>
</tr>
<tr>
<td>R18</td>
<td>150K ohm</td>
</tr>
<tr>
<td>R19</td>
<td>330K ohm</td>
</tr>
<tr>
<td>R21, R23</td>
<td>33K ohm</td>
</tr>
<tr>
<td>R22</td>
<td>1.8K ohm</td>
</tr>
<tr>
<td>R24</td>
<td>47K ohm</td>
</tr>
</tbody>
</table>

**Capacitors**

- C1, C3, C5, C6, C7, C9, C13 - 0.05 microfarad
- C2, C4, C11 - 2000 picofarad
- C8 - 60 picofarad
- C10, C12 - 1000 picofarad
- C14 - 220 picofarad
- C15, C16, C17 - 10 microfarad

**Diodes**

- D1-D4 - any germanium diode
- D5 - any silicon diode

**Filters**

- F1 - muRata CFU455F2

**Coils**

- T1, T2 - 455 kHz transformers, 40K ohm primaries—secondaries not connected; adjusted to provide as flat a response as possible from 450-460 kHz
Transistors

Q1, Q2 - Radio Shack RS2010
Q3, Q4, Q5 - Radio Shack RS2015
Q6, Q8 - 2N2222
Q7 - Radio Shack RS2022
Graph 2

\((0.7 + av) \) vs. \(V\)

\(a = 0.75\)

\(a = 0.5\)

\(a = 1.33\)
\[ \left( \frac{.7 + v}{.7 + av} \right)^{1\alpha} \text{ vs. } v \]
RECEIVER SPECIFICATIONS

TUNING RANGE:  540-1600 kHz
TUNING METHOD:  Electronic, digitally controlled
IF FREQUENCY:  455 kHz
ANTENNA TYPE:  Ferrite rod
SELECTIVITY:  25 dB adjacent channel (10 kHz)
               >60 dB alternate channel (20 kHz)
IMAGE REJECTION:  >60 dB at 600 kHz
                  55 dB at 1400 kHz
IF REJECTION:  >60 dB at 1000 kHz
REFERENCES


