THE DESIGN, CONSTRUCTION, AND ANALYSIS OF A RECEIVER-FREQUENCY STANDARD

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THE DESIGN, CONSTRUCTION, AND ANALYSIS OF A RECEIVER-FREQUENCY STANDARD

By

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A THESIS

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CHAPTER I

THE PROBLEM

The original thesis project, as assigned, was to build a radio frequency signal generator, of sufficient accuracy and stability to be used as a frequency standard for the laboratory of Michigan State College.

Now it is the duty of the engineer to design his equipment, not only with the finest possible result in mind, but also with an eye to cost. An excellent design might be useless from a practical standpoint, due to prohibitive cost of construction. On the other hand, by cutting expenses too closely, an inferior product will result. The engineer who performs his task best is the one who strikes the finest balance between these two extremes, producing an article which will amply fulfill the desired service for the smallest possible expenditure.

It was with this thought in mind, that methods to produce this stable signal were considered.

METHODS OF SOLUTION

The crystal controlled oscillator. Using a crystal controlled oscillator, with careful voltage regulation and a narrow limit, temperature controlled oven, accuracies of about one parts in 10^6 are possible from a laboratory built generator.[1]

The receiver-frequency standard. The National Bureau of Standards station in Washington D.C., WWV, transmits various signals with an accuracy of two parts in 10^8.[2] The received signals are subject to Doppler effect due to variations in the height of the ionosphere, which may be as great as two parts in 10^8. The maximum error of the received signal will then be four parts in 10^8. A sensitive receiver could be built for these signals, that would amplify them to a magnitude suitable for a laboratory frequency standard.

Comparison and choice. The crystal controlled oscillator, with all the necessary refinements to produce a stable frequency, is an expensive project. Furthermore, in operation, it would require continual checking, and possibly adjusting, to maintain its accuracy. The receiver for the Bureau of Standards transmissions, on the other hand, could be constructed for only a fraction of the cost of the oscillator, require only occasional alignment, and would be absolutely dependable, with respect to frequency

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[1] Issac Koga, "Notes on Piezoelectric Quartz Crystals," Proceedings of the Institute of Radio Engineers, 24:530, March, 1936

[2] Letter Circular LC886, U.S. Department of Commerce, National Bureau of Standards, Central Radio Propagation Laboratory, Washington, D.C., 1948, P.1.

stability, within the accuracy of the received signal. For these reasons, the receiver type standard was chosen for this project.

The design and construction of a receiver to accomplish this service to best advantage are somewhat different from those of a conventional receiver, and some unusual problems are posed.

The remainder of this work deals with these problems, and the methods by which they were solved.

CHAPTER II

GENERAL DESIGN CONSIDERATIONS

Using a receiver for the Bureau of Standards transmissions as a frequency standard presents several difficulties, most of which can be fully, or at least partially, overcome by the proper design of the receiver.

Problems to be encountered. The major difficulties are as follows:

1. Drift of tuned ciruits in the receiver may cause shift in output frequency or amplitude.
2. Fading of the signal may cause annoying variations in the magnitude of the signal output.
3. Atmospheric conditions, cosmic radiation, local interference, etc. may cause severe noise impulse interference.
4. Adjacent channel or image interference may give rise to spurious responses.
5. The amplitude modulation which is superimposed on the signal will give rise to sum and difference frequencies which may be confused with the desired signal.

Methods for solving these problems. These difficulties may be attacked in the following manner:

1. By using a tuned-radio-frequency receiver instead of the more common superheterodyne, the problem of frequency drift of the output signal is immediately solved. With no local oscillator beating against the signal input, the output frequency cannot possibly drift. There remains only the problem of keeping the circuits tuned to the incoming signal. By the use of high quality coils and

condensers, combined with a band width that is not too narrow, this is readily accomplished. There no longer need be any concern about voltage regulation, temperature, or humidity changes. With this type of receiver, the severest changes in these bugaboos of frequency stability, can cause no more harm than a slight change in signal output amplitude, a factor that can be readily corrected for by other means. Also, this type of receiver is not subject to image interference, so one more problem is eliminated.

2. Fading of the signal can be easily compensated for by incorporating sufficient amplification in the design so that full output can be achieved on the weakest signal expected, and automatic volume control, or limiting used to prevent its rising above this level. Effective limiting will also tend to square the wave form sufficiently to give usable harmonics up to many times the signal frequency.
3. Noise impulses can be minimised in the output by effective limiting and narrow band-pass.
4. Adjacent channel interference can be minimised by using steep sloped band-pass coupling circuits, in sufficient number so that the attenuation of adjacent signals will be very great.
5. The undesirable amplitude modulation can be removed by the limiting circuit, along with the noise impulses.

It was also decided that it would be desirable to be able to detect the signal received so that a quick check could be made on the reception by listening to the audio modulation frequencies. To accomplish this end, a detector, audio amplifier, and loud speaker will be added to the receiver. This should be so designed as not to interfere with the primary radio frequency output in any way. The standard one second time pulses and audio signal may then be used for many purposes, such as operating an accurate time piece, or checking the accuracy of audio oscillators. A switch should be placed in the loud speaker so that the output can be used for these purposes without the audible sound, when so desired.

Overall plan. A general picture of the receiver that will satisfy these design requirements can now be drawn:

1. It will be a tuned-radio-frequency receiver.
2. It must have sufficient amplification to achieve full output on the minimum signal strength expected.
3. It must incorporate a limiter stage, and perhaps automatic volume control as well.
4. High quality, narrow skirted band-pass coils must be used for interstage coupling.
5. A voltage regulated power supply is not necessary.

CHAPTER III

SPECIFIC DESIGN CONSIDERATIONS

Signal to be received. At this point it would be well to include some information about the signals which may be received from WWV. The following table describes the signals transmitted from this station:[3]

Megacycles	Power in KW.	Modulation in cps.
2.5	0.7	1 and 440
5	8.0	1 and 440
10	9.0	1, 440 and 4000
15	9.0	1, 440 and 4000
20	8.5*	1, 440 and 4000
25	0.1	1, 440 and 4000
30	0.1	1 and 440
35	0.1	1

* .1 KW. for first four work days after first Sunday of each month.
All transmissions continuous day and night.

Since a tuned-radio-frequency receiver is being designed, gain and adjacent channel selectivity are most easily achieved at lower radio frequencies. The power of the lowest frequency transmission, however, is less than one tenth of that of the two next higher frequencies, and so it was discarded. Either the five or the ten megacycle signal would suit the purpose admirably. Since some well designed five megacycle band-pass coils (later described in detail) were

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[3] National Bureau of Standards, *loc. cit.*

already available in the laboratory, this frequency was decided on for the signal standard.

The signal strength of this transmission, in the East Lansing area averages about 400 microvolts per meter.[4] Assuming that under the most adverse conditions of extreme fading, the signal strength might drop to five microvolts per meter, it was decided to design the receiver for full output capabilities when the signal strength is five microvolts per meter and the antenna only one meter long. This sensitivity is achievable, and will assure full output under the worst expected conditions.

Coils to be used. Since the heart of any radio frequency receiver is in its coils, the design will be begun by examining these carefully.

The usual design procedure is somewhat reversed in this case. Ordinarily the receiver is designed, and then coils are built to satisfy the design requirements. In this case however the coils were already available, and it became necessary to design a receiver that would operate successfully with these coils. Happily, this was not too difficult a task, since the coils were well designed, and suited admirably to the purpose. They are solenoid wound on a ceramic form five-eights of an inch

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[4] Personal Correspondence of the Author, letter from V. E. Heaton, February 17, 1949.

in diameter. The two windings are identical, and both trimmed with air capacitors having screw-driver adjustments.

The following measurements were made on the coils (in shield) with the department Q meter:

At 5mc., Q 130.
At 3.44 mc., with coils in series aiding,
C 33.85 mmf. to tune.
At 3.44 mc., with coils in series opposing,
C 35.00 mmf. to tune.

From these data the significant findings are:

Q of each coil at 5 mc. 130.
Inductance of each coil .0308 mh.
Mutual inductance between coils .0006 mh.
Capacitance to tune circuit to 5 mc. 33 mmf.

These figures will be used later to compute stage gain.

It was decided that an untuned primary would be preferable for the antenna input coil, since this method allows for greater flexibility in antennas. The apparatus will be used in various locations, and it would be very desirable to be able to use any antenna available at the time. If the primary were tuned, this circuit would require realigning for each antenna. A closely coupled, untuned primary will cause only second order detuning and higher signal to noise ratio than a loosely coupled, double tuned stage. A coil that was expressly designed for this purpose, and having a gain of six, was available and was decided upon in preference to the other for the antenna coupling coil.

R.F. STAGES

Choice of tubes. Much consideration was given to the choice of vaccuum tubes for the R.F. Stages. The following items govern this choice:

1. Stability (need for neutralizing grid-plate capacitance).
2. External shielding.
3. Signal to noise ratio (first stage only).
4. Stage gain.
5. Cross modulation (last stage only).
6. Ability to utilize automatic volume control effectively.

These items will now be considered:

1. The obvious choice is the use of a radio frequency pentode, since this type of tube includes a shield between the plate and and signal grid. This reduces the capacitance between these two elements to a value such that neutralization usually becomes unncessary.[5]
2. An internally shielded, or metal, tube is required to eliminate the need for separate external shields on each tube to prevent feedback between stages and oscillation. It has been the experience of the author to find that the metal tubes afford better shielding, and they are preferred for this reason.
3. Since the design is to be for a minimum signal of five micro-volts, and the antenna coil

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[5] William Littell Everitt, Communications Engineering (New York: McGraw-Hill Book Company, Inc., 1937), P.513.

gain is six, a minimum of thirty microvolts of signal will be applied to the first grid.

3. Since the equivalent noise voltage referred to the grid of an radio frequency pentode is of the order of one or two microvolts,[6] this factor can be neglected. The tube noise will always be completely masked by the signal.
4. The mutual conductance of radio frequency pentodes ranges in general from about one thousand to nine thousand micromhos.[7] Extremely high gain tubes always present the problem of regeneration, and require very careful stage design. The use of these tubes will reduce the number of stages needed to achieve the necessary gain but that is not desirable in this case, as reducing the number of tuned circuits will broaden the response curve. For these reasons extremely high gain tubes were ruled out. On the other hand, the lowest gain tubes will necessitate too many stages, and lead to a cumbersome product. A medium high gain tube is therefore to be preferred.
5. In order that a tube may handle large signals without cross-modulation, it must have no sharp discontinuities in its grid voltage versus plate current curve. To accomplish this end, the tube must be designed with a gradual, rather than a sharp cut off characteristic.
6. The ability of a tube to utilize automatic volume control effectively is also dependent on its cut off characteristic. A gradual curve is necessary to prevent cross-modulation. Therefore a tube with a remote cut off should be chosen.

From these considerations, the 6SG7 tube is well suited for this application. Its salient features are:[8]

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[6] Karl R. Spangenberg, Vacuum Tubes (New York: McGraw-Hill Book Company, Inc., 1948), P.327.

[7] Ibid.

[8] Receiving Tube Manual, (RCA Manufacturing Company, Inc., 1940), P.234.

1. Radio frequency pentode.
2. Screen grid shielding between grid and plate, bringing the capacitance between these two elements down to a maximum of .003 micro-microfarads.
3. Metal envelope and conical stem shielding.
4. Separate cathode connections for improved isolation between input and output circuits.
5. Fairly high gain (mutual conductance of 4000 micromhos).
6. Cut off extended to -17.5 volts.

Stage gain. Using this tube, and the previously described coils, the stage gain and band-width that may be expected can now be found:

The formula for calculating stage gain is:[9]

$$\frac{e_o}{e_i} = \frac{g_m\sqrt{R'R_2}}{K\sqrt{Q'Q_2} + \frac{1}{K\sqrt{Q'Q_2}}}$$

Where:

e_o = Output voltage to following grid.
e_i = Input voltage to grid.
gm = mutual conductance.
k = Coupling factor.
r_p = Plate resistance of tube.
Q_1 = Q of primary circuit.
Q_2 = Q of secondary circuit.
R_1 = Equivalent tuned circuit resistance of primary.
R_2 = Equivalent tuned circuit resistance of secondary.

$$\frac{1}{Q'} = \frac{\omega_0 L_1}{r_p} + \frac{1}{Q_1}$$

$$\frac{1}{R'} = \frac{1}{r_p} + \frac{1}{R_1}$$

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[9] F. Langford Smith, editor, *The Radiotron Designer's Handbook* (third edition; Sidney, Australia: Wireless Press, 1940), P.122.

The formula for calculating R_1 and R_2 is:[10]

$$R = Q\sqrt{\frac{L}{C}}$$

The formula for calculating K is:[11]

$$K = M/\sqrt{L_1 L_2}$$

Solving these equations with the known values for the 6SG7 tube and the given coils, the following data are found:

R = 125000 ohms.
R = 125000 ohms.
k = .02.
Stage gain = 156.

In practise, however, this theoretical gain may not be realizable. The frequency at which the stage is to operate has not been taken into account in these calculations. At high frequencies the grid-plate capacitance plus the unavoidable minimum wiring capacitance presents a feedback path which can lead to instability. The maximum stable gain of a single stage, when limited only by the grid-plate capacitance, is found by the following formula:[12]

$$\text{MAX. GAIN} = \sqrt{\frac{g_m}{\pi C f}}$$

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[10] *Ibid.*, P.119.

[11] *Ibid.*, P.121.

[12] Technical Advertising Associates, *Radio Component Handbook* (Philadelphia: Dunlap Printing Company, 1948), P.51.

Where:

gm = Mutual conductance of tube.
c = Grid-plate capacitance of tube.
f = Frequency of operation.

For the 6SG7 tube operating at five megacycles this gain is 291. Unavoidable tube socket and wiring capacitance will reduce the stable gain to about one-half of this value, or 145. Fortunately then, the gain need not be very greatly reduced in the interest of stability.

Now assuming that a limiter can be devised to operate satisfactorily on a five volt signal input, and that the incoming signal will not be less than five microvolts, an overall radio frequency gain of 1,000,000 will be necessary. The antenna coil affords a gain of six; and so the amplifier bank will have to deliver a gain of about 200,000. Three stages, each with a gain of 140 will have an overall gain of $(140)^3$ which is 2,750,000, or more than ten times the gain needed. It will be advantageous then, to use three stages and to reduce the gain of each stage somewhat, so that it will be operating more conservatively. It will therefore require fewer tube replacements and achieve greater stability.

To return now to the coils, an actual check on their response using a signal generator and vacuum tube voltmeter indicates that there is no double peaked resonance.

Since critical coupling for the coil is:[13]

$$K_c = \frac{1}{\sqrt{Q_p Q_s}} = .0077$$

and the coupling found by Q meter test is .02, it would be expected that a double peaked resonance would be found. This apparent contradiction is not surprising, as the Q meter test did not take into account the capacitive coupling, which is obviously opposing the mutual inductance and of almost the same magnitude. Since the total effective coupling is not as great as was assumed for the gain calculations, it is to be expected that the actual gain will be somewhat greater than the result found. This fact need not be disturbing, as the tube gain can easily be adjusted by bias, so that the desired result will be obtained.

Band-width. The calculation of band-width is a very laborious procedure; and it is far more convenient to use a set of universal selectivity curves.[14]

Since no double peak was found it was assumed that the coupling is approximitely equal to the critical value. In finding the band-width it was assumed that

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[13] Smith, *op. cit.*, P.122.

[14] Frederick Emmons Terman, *Radio Engineers' Handbook* (New York; McGraw-Hill Book Company, Inc., 1943), P.160.

critical coupling exists between the coils.

Using the curves for double-tuned circuits, the following data were found:

Kilocycles off resonance	Attenuation (db.)
19	1
25	2
32	4
38	6
45	12

The antenna coil requires the use of selectivity curves for single-tuned circuits. From these curves the following data were found:[15]

Kilocycles off resonance	Attenuation (db.)
19	2
25	3
32	4
38	5
45	6

Since there are to be three double-tuned and one single-tuned circuits, the overall response will be:

Kilocycles off resonance	Attenuation (db.)
19	5
25	9
32	16
38	23
45	42

A somewhat sharper nosed curve might be desired; however, since the signal strength expected is strong, it should be able to over-ride any interference at very close to resonant frequency. The skirts are

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[15] Smith, *op. cit.*, P.129.

very narrow and any signal more than thirty kilocycles off the peak will almost certainly be completely attenuated.

THE LIMITER

Various types of limiters and clippers were tested with varying degrees of success. The types which depend on anode bend or saturation for their operation were found to be unsatisfactory on the whole. The cut off was not abrupt enough on any tube experimented with, and even when the signal was large enough to assure complete limiting, the wave form was rounded and not at all rich in the desired harmonics.

The most satisfactory method was the use of the simple double-diode clipper. An adaptation of this circuit was devised, wherein the grid of a pentode tube acted as both the signal injector and the diode plate, while a conventional diode cathode operated on the lower portion of the curve to afford full wave clipping in the most economical fashion.

The complete circuit diagram, (see table of contents), illustrates the circuit. The voltage A+, (indicated on the diagram), may be made any value to determine the threshold of clipping. A value of about one volt was decided upon, as this is low enough to assure limiting and high enough to assure full output.

The stage gain and clipping action were both found to be excellent.

FINAL DESIGN CONSIDERATIONS

The output. The output must be capable of operating into a variety of loads without any severe disturbances of the circuit. To accomplish this end, a cathode follower was decided upon. This type of output is stable, supplies considerable amounts of power, and is not affected to any great extent by load variations.

The screen grids. The screen grids of the radio frequency stages were supplied from a fixed voltage source. This system will sometimes cause cross-modulation on strong signals, due to the fact that the remote cut off is somewhat sharpened.[16] It was chosen, in spite of this drawback, for the following reasons:

1. Automatic volume control is most effective when the screen voltages of the controlled stages are fixed.
2. Since three stages are controlled, the signal variation on any stage will be small.
3. The radio frequency amplifying tubes chosen are not prone to cross-modulation effects except when handling very large signal voltages.
4. Since only one radio frequency is to be received, the signal strength variations should not be very great. Therefore overloading should present no problem.

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[16] Smith, *op. cit.*, P.204.

Other circuits. The audio circuits, power supply, etc. are conventional in design and need no description other than that supplied by the complete circuit diagram.

The chassis. The chassis chosen was seventeen by eleven inches, a size that will fit conveniently on a rack panel mounting.

Layout of parts. The layout of parts was so arranged as to afford a neat construction with a minimum of sources of exteraneous coupling. To further this end, no radio frequency stage grid or plate lead is more than one half inch long, and the detector, clipper, and radio frequency output circuits are further isolated with copper shields.

CHAPTER IV

TEST RESULTS

Sensitivity. As was predicted in chapter three, the sensitivity of the receiver-frequency standard can be easily adjusted by bias control of the radio frequency stages. It was found that regeneration became objectionable when the sensitivity was increased beyond five microvolts. It was therefore fixed at this value. A thirty percent, four-hundred cycle-per-second modulated signal was used for testing. This signal is just audible at one microvolt input. At five microvolts the audio output is ample for any application that may be desired.

Selectivity. The selectivity of the receiver-frequency standard is slightly poorer than predicted; however the difference is quite small. It is possible that the coefficient of coupling between the coils was correct as determined by the Q meter test, and that the double peaked curve failed to appear due to the heavy loading effect of the inferior vacuum tube voltmeter used.

Radio frequency output. The radio frequency output could not be measured by any equipment available in the laboratory. The vacuum tube voltmeter loaded very badly at five megacycles, and caused feedback and instability to occur due to poor shielding. The frequency meter radiates its own signal which is capable of completely over-riding WWV when set at five megacycles. All that can be said about the radio frequency output is that it must exist, or there could be no cause for regeneration when the vacuum tube voltmeter is connected to it.

DATA

The following data were taken by direct measurment on the completed receiver - frequency standard:

Sensitivity characteristic. Input in microvolts, thirty percent modulated, four-hundred cycles-per-second. Output in volts at high impedence audio jack.

Microvolts input	Volts output	Microvolts input	Volts output
0	0	50	33
1	2.1	70	38
2	4.5	100	42
3	6.2	150	47
4	7.4	200	50
5	8.7	300	54
7	11.2	500	59
10	13.7	1K	65
15	16.3	5K	81
20	19.2	10K	84
30	24.5	50K	93
40	29.0	100K	99

Selectivity characteristic. Input in microvolts, thirty percent modulated, four-hundred cycles-per-second. Bandwidth found for fixed output of ten volts at high impedence jack.

Microvolts input	Band-width KC.	Microvolts input	Band-width KC.
100	0	1K	120
200	40	2K	150
300	80	5K	180
400	100	10K	200
500	110	50K	260
700	112	100K	290

Voltages at tube socket terminals. Measured with vacuum tube volt meter.

Tube type	Purpose	Pin Number			
		1	2	3	4
6X5	Rect.	NC	0	270	NC
6SG7	1st. R.F.	0	7*	6.3	-0.3
6SG7	2nd. R.F.	0	7*	5.7	-0.3
6SG7	3rd. R.F.	0	7*	4.2	-0.3
6H6	Det. AVC.	0	7*	-0.6	0
6SJ7	Clipper	0	7*	1.5	0
6J5	Cath. Foll.	0	0	120	NC
6SN7	Audio	0	285	9.6	0

Tube type	Purpose	5	6	7	8
6X5	Rect.	270	NC	7*	340
6SG7	1st. R.F.	6.3	140	0	287
6SG7	2nd. R.F.	5.7	140	0	285
6SG7	3rd. R.F.	4.2	140	0	280
6H6	Det. AVC.	0	NC	0	0
6SJ7	Clipper	1.5	84	0	45
6J5	Cath. Foll.	0	290	7*	4
6SN7	Audio	120	5.8	7*	0

*Sixty cycles AC.

Resistances from tube socket terminals to ground.

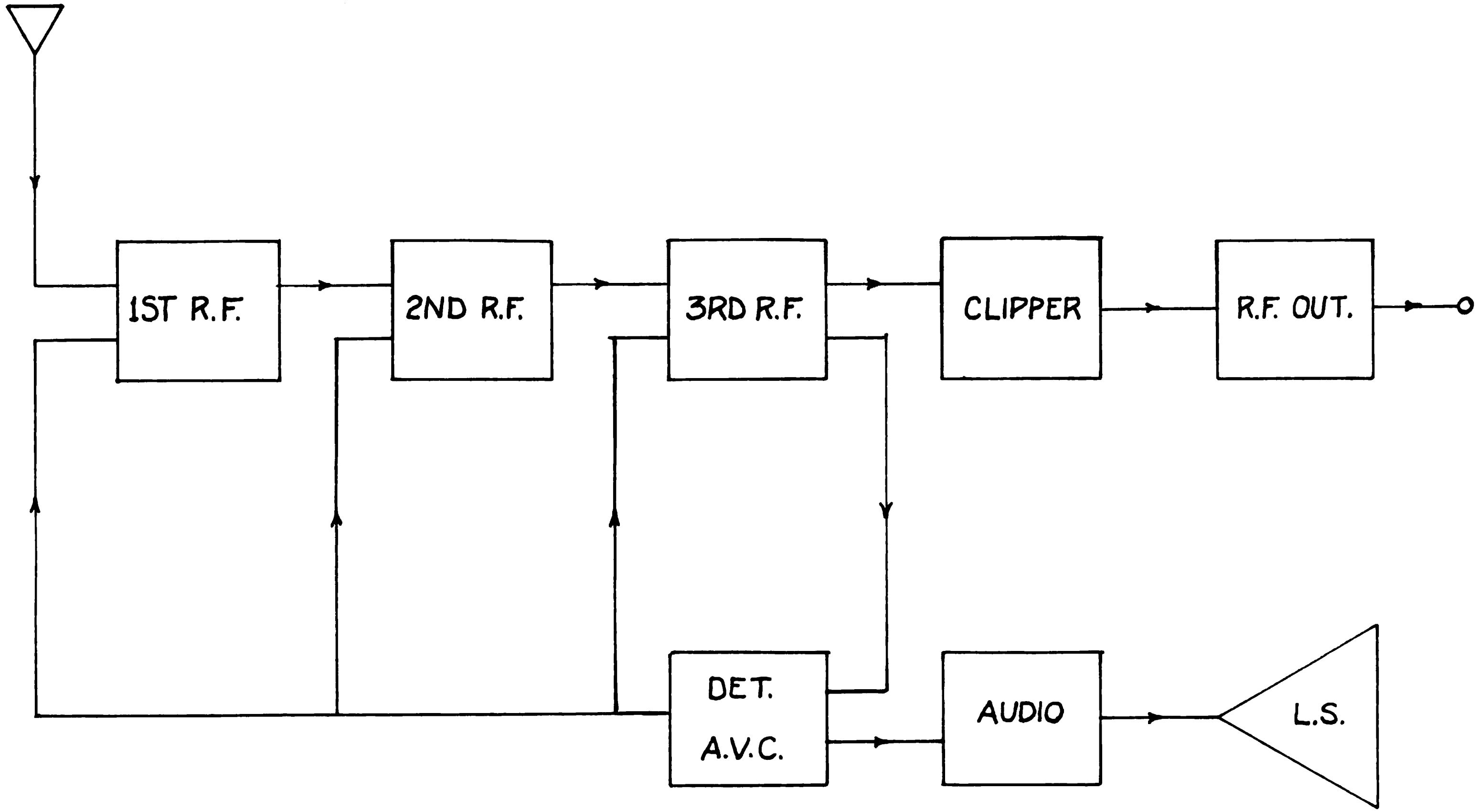
Tube type	Purpose	Pin Number 1	2	3	4
6X5	Rect.	NC	0	80	NC
6SG7	1st. R.F.	0	0	3.5K	1.3M
6SG7	2nd. R.F.	0	0	2K	1.3M
6SG7	3rd. R.F.	0	0	1K	1.3M
6H6	Det. AVC.	0	0	.2M	0
6SJ7	Clipper	0	0	100	.4
6J5	Cath. Foll.	0	0	75K	NC
6SN7	Audio	.5M	.27M	1K	.5M

Tube type	Purpose	5	6	7	8
6X5	Rect.	75	NC	0	2.4K
6SG7	1st. R.F.	3.5K	28K	0	27K
6SG7	2nd. R.F.	2K	28K	0	27K
6SG7	3rd. R.F.	1K	25K	0	24K
6H6	Det. AVC.	0	NC	0	.4
6SJ7	Clipper	100	70K	0	85K
6J5	Cath. Foll.	10K	27K	0	1K
6SN7	Audio	.27M	10K	0	0

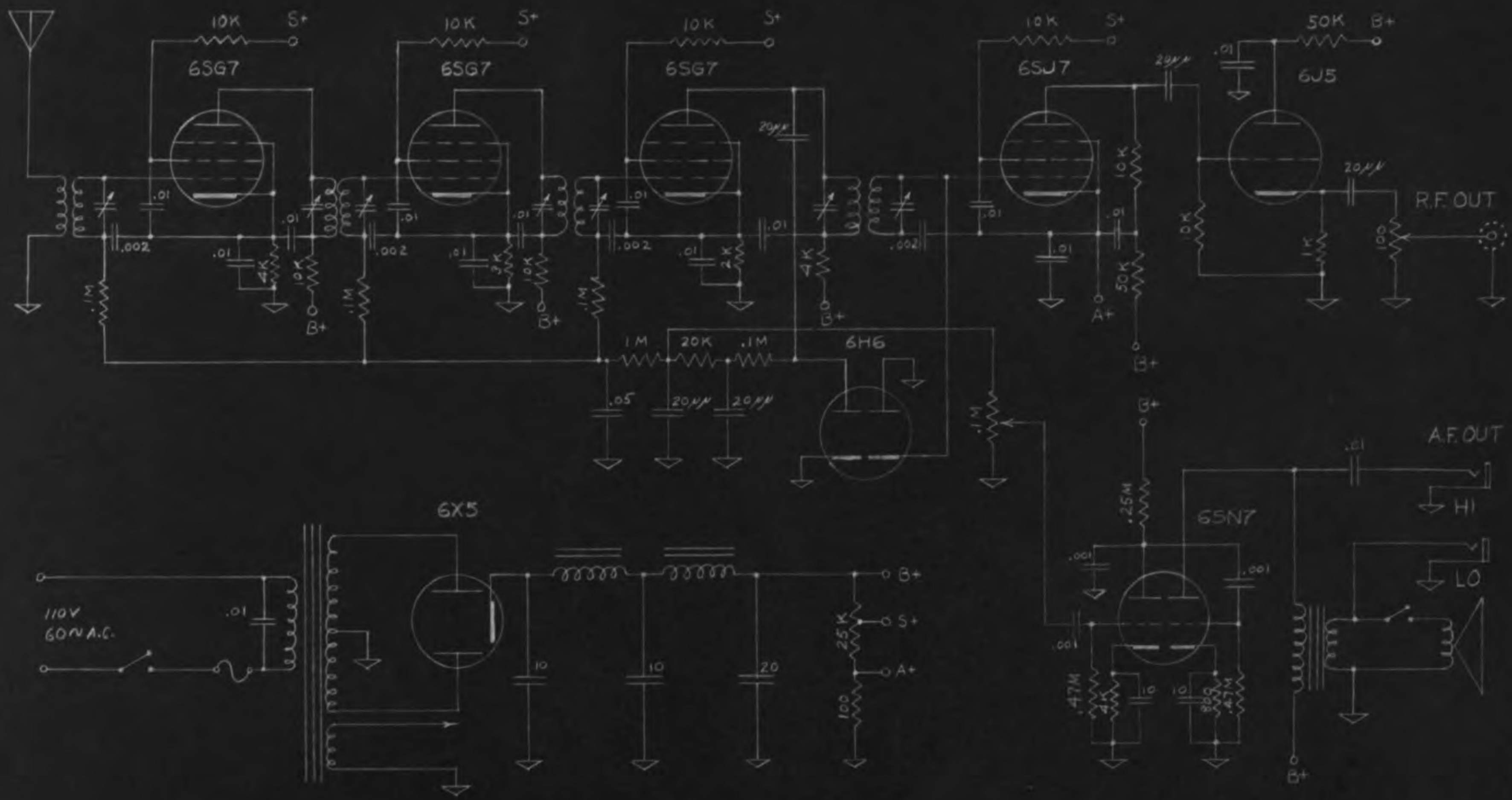
DIAGRAMS, ILLUSTRATIONS AND CURVES

The following illustrations present pictorially the complete electrical and mechanical design and performance of the receiver frequency standard, beginning with the block diagram which indicates the general purpose of the various parts of the apparatus, through to the photographs of the finished equipment.

BLOCK DIAGRAM

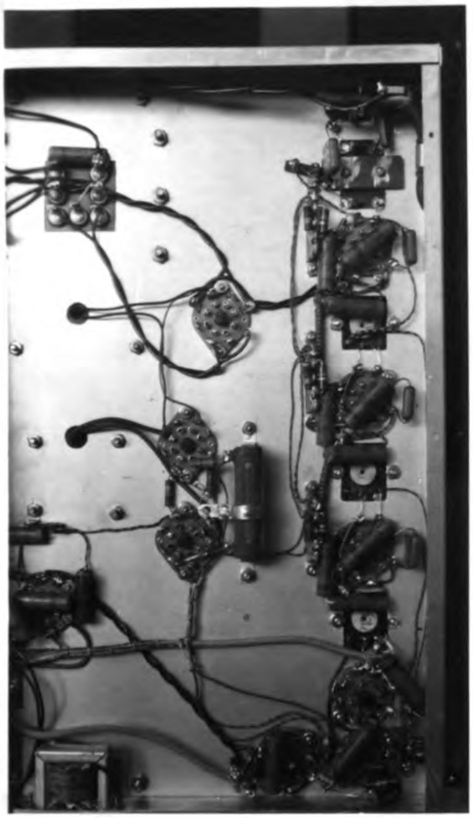


COMPLETE CIRCUIT DIAGRAM

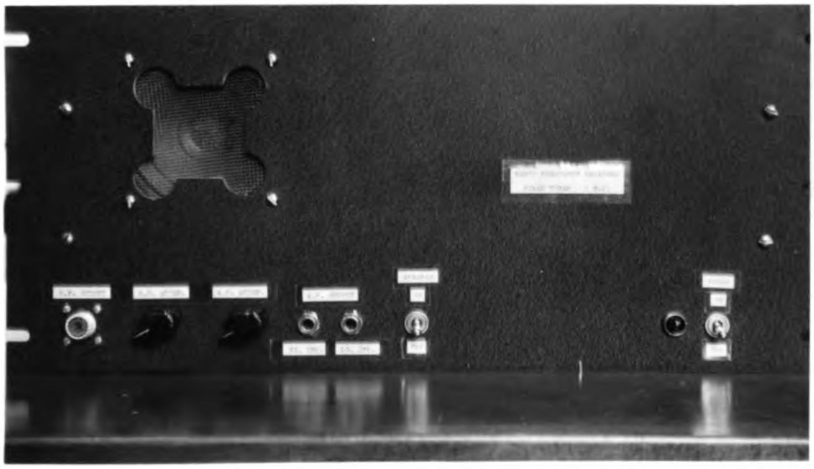


PHOTOGRAPHS

Top view



Bottom view
(Shield removed)



Front view

CHAPTER V

CONCLUSIONS

The operation of the receiver-frequency standard is satisfactory on the whole, but several improvements that could be made are apparent.

In the environs of East Lansing, the five megacycle signal from WWV does not have the signal strength expected. The ten megacycle signal would be more satisfactory from this standpoint, and could be used to better advantage. Of course, in areas less distant from Washington D.C. this objection would no longer exist.

The broadnosed response curve of the receiver offers little adjacent-channel and noise rejection. A greatly reduced coefficient of coupling between the double tuned coils, plus a higher tube gain to make up for the less incurred, would improve this characteristic.

Due to the fact that a very high overall gain is accomplished at one radio frequency, the tendency to instability was difficult to overcome. Separate shielded containers for the circuits associated with each stage were warranted, but not absolutely necessary. In particular, the radio frequency output circuit had to be very well shielded and completely isolated from all the other circuits, or regeneration would have certainly become objectionable.

The stable frequency was obtained; the cost was held within low limits; and all indications tend to show that the receiver-frequency standard is a practical and desirable instrument.

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