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A VELOCITY COMPENSATOR FOR MTI

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A VELOCITY COMPENSATOR FOR MTI

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March 2, 1949

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ABSTRACT

The theory underlying the coho frequency-shift method of compensating a coherent MTI for own ship's motion is discussed, and the important mathematical relations are developed.

A Velocity Compensator - designed for use in the MTI Conversion Unit for SR-3 and SPS-6 Radars - which will compensate without loss in subclutter visibility for ship speeds up to 33 knots, and with a loss of about 5 db at a speed of 40 knots, is described.

PROBLEM STATUS

This is an interim report on this problem; work is continuing.

AUTHORIZATION

NRL Problem R02-24 (BuShips Problem S1055R-C)

Glossary of Symbols

c = velocity of propagation of electromagnetic waves in a vacuum = 6.7×10^{8} mph

f_c = coherent oscillator frequency

f_{cc} = velocity compensated coherent oscillator frequency

f_d = doppler frequency

f_{ds} = doppler frequency due to own ship's motion

f_{dt} = doppler frequency due to target's motion

f_o = transmitted frequency

f_s = coho frequency shift necessary to compensate for own ship's motion

Δf_s = error in coho compensation frequency

PRF = pulse repetition frequency

R_{max} = maximum permissible subclutter visibility

S_r = relative sensitivity

$V_{max}^{(n)}$ = speed for maximum response where n is the order of the maximum

$V_{null}^{(n)}$ = speed for no response where n is the order of the null

ν_s = ship's velocity

$\nu_s^{(r)}$ = component of ship's velocity in direction of target under consideration

$\nu_t^{(r)}$ = radial component of target's velocity

θ_b = beamwidth of radar antenna

θ_e = effective clutter beamwidth of antenna (see footnote 4 page 6)

θ_r = relative bearing of antenna beam

A VELOCITY COMPENSATOR FOR MTI

INTRODUCTION

Problem

One of the most serious problems encountered in the application of MTI to high-frequency radars for shipboard use is the problem of velocity compensation for own ship's motion. The use of MTI on such radars generally gives a first speed of peak response ($V_{max}^{(1)}$) of well under 100 knots, with the result that a ship's speed of 30 to 40 knots gives considerable MTI response from fixed targets. In order to remove this unwanted response, the MTI system must be modified in a manner such as to make it sensitive to motion relative to a stationary base rather than to the moving (radar-carrying) ship.

A unit for thus modifying the MTI system response has been developed at this Laboratory for use in the MTI Conversion Unit for SR-3 and SPS-6 Series Radars.

References

This report will be concerned mainly with the theory of, and circuitry for, velocity compensation of a coherent Moving Target Indicator (MTI) system by means of coho shift, and is therefore simply an extension of NRL Report No. R-3246, which goes in detail into the basic theory of pulse-doppler radar.[1] For this reason many equations found herein are taken directly from R-3246, and for ease in following the continuity between these two reports, all such equations have been given the same numbers (below 100) they bear in R-3246, and all new equations derived have been given numbers in the 100 series.

Attention is also called to a forthcoming NRL report which will describe the complete MTI Conversion Unit for the SR-3 and SPS-6 Series Radars for which the present velocity compensator was developed.

THEORETICAL CONSIDERATIONS

Magnitude of Compensating Frequency

In order to compensate a coherent MTI system to detect motion relative to a stationary point (rather than to the radar-carrying ship), the frequency shift (f_s) introduced into the coho signal must be the same magnitude as, and in the same direction as, the doppler shift (f_d) introduced into the frequency of an echo returning from a stationary target by the motion of the ship relative to that target.

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[1] T. H. Chambers, "The MTI Conversion Unit for SC-SK Series Radars," NRL Report R-3246, March 2, 1948, (Confidential)

A well-known equation for the doppler shift in the MTI case is

$$f_d \cong \frac{2\,\nu_s^{(r)} f_o}{c}\ , \tag{16}$$

where

f_d = doppler frequency shift (due in this case, to ship's motion),

$\nu_s^{(r)}$ = component of ship's velocity in direction of target,

c = velocity of light,

f_o = radar frequency.

But

$$\nu_s^{(r)} = \nu_s \cos\theta_r,$$

where

ν_s = ship's forward speed,

θ_r = relative bearing of antenna.

Substituting for $(\nu_s^{(r)})$,

$$f_d \cong \frac{2\,\nu_s f_o}{c} \cos\theta_r\ . \tag{16.1}$$

This is the doppler shift introduced by the ship's motion, and since

$$f_s = f_d,$$

Then

$$f_s \cong \frac{2\,\nu_s f_o}{c} \cos\theta_r. \tag{16.1a}$$ [2]

Under some conditions, this equation will be more useful in terms of $V_{null}^{(1)}$ and (PRF). Thus,

$$V_{null}^{(1)} = \frac{(PRF)c}{2 f_o} \tag{13}$$ [3]

---

[2] The a following the equation number denotes an equation taken from NRL Report R-3246, but with a more general variable substituted.

[3] With n = 1.

Rearranging terms,

$$\frac{2 f_o}{c} = \frac{PRF}{V_{null}^{(1)}}.$$

Substituting this in equation 16.1a,

$$f_s \cong \frac{\nu_s (PRF)}{V_{null}^{(1)}} \cos \theta_r . \tag{16.2}$$

where

f_s = coho shift necessary to compensate for ship's motion.

The compensated coho frequency will then be

$$f_{cc} = f_c + f_s$$

where

f_{cc} = compensated coho frequency,

f_c = coho frequency.

Attention should be called to the fact that, although f_s has been discussed as a frequency shift, it is more important to consider it as a continuous phase rotation of the original coho signal. Thus, the initial phasing of the coho must be accurately preserved, and compensation must consist of the addition of a controlled amount of phase rotation in a given period of time.

Accuracy of Compensation

The accuracy which is required of the coho shifting means will now be investigated. Consider equation 14,

$$S_r = \left| \sin \frac{2 \pi \nu_t^{(r)} f_o}{(PRF) c} \right|, \tag{14}$$

where

S_r = relative sensitivity,

$\nu_t^{(r)}$ = target radial velocity,

f_o = transmitted frequency,

(PRF) = pulse repetition frequency,

c = velocity of light.

This equation gives the sensitivity of the MTI system in terms of the target's radial velocity. It may be rewritten as

$$S_r = \left| \sin \frac{\pi}{(PRF)} \left(\frac{2\,\nu_t^{(r)}}{c} f_o \right) \right| \tag{14}$$

But, by equation 5 (reference 1),

$$\frac{2\,\nu_t^{(r)}}{c} f_o \cong f_d \,, \tag{5}$$

where

$$f_d = \text{doppler frequency.}$$

Substituting this in equation 14, we get

$$S_r = \left| \sin \frac{\pi f_d}{(PRF)} \right| . \tag{101}$$

Thus, we have the sensitivity of the system in terms of the doppler shift.

It must, however, be remembered that this doppler shift is a difference in frequency and not a detectable single frequency. Thus, in the case of a velocity-compensated MTI system,

$$f_d = f_r - f_{cc}, \tag{102}$$

where

$$f_r = \text{received echo frequency,}$$

$$f_{cc} = \text{compensated coho frequency.}$$

In the MTI case,

$$f_r = f_o + f_{dt} + f_{ds}, \tag{103}$$

where

$$f_{dt} = \text{shift due to target's motion, and}$$

$$f_{ds} = \text{shift due to ship's motion;}$$

and

$$f_{cc} = f_c + f_s + \Delta f_s \tag{104}$$

where

$$f_c = \text{coho frequency} = f_o,$$

$$f_s = \text{coho compensating frequency} = f_{ds}, \text{ and}$$

$$\Delta f_s = \text{error component of coho compensation.}$$

Then, substituting equations (103) and (104) in equation (102),

$$f_d = (f_o + f_{dt} + f_{ds}) - (f_c + f_s + \Delta f_s); \qquad (102.1)$$

and since

$$\begin{cases} f_c = f_o \\ f_s = f_{ds}, \end{cases}$$

then

$$f_d = f_{dt} - \Delta f_s. \qquad (102.2)$$

But, in the case of a stationary target,

$$f_{dt} = 0;$$

so,

$$f_d = - \Delta f_s.$$

Substituting this in equation 101, we get

$$S_r = \left| \sin \frac{-\pi \Delta f_s}{(PRF)} \right| .$$

But since,

$$\sin(-x) = -\sin(x),$$

and we are taking the absolute value,

$$S_r = \left| \sin \frac{\pi \Delta f_s}{(PRF)} \right| . \qquad (105)$$

In this case, S_r is the sensitivity of the system relative to an error in the compensation of the coho frequency.

This sensitivity may be converted to a maximum permissible subclutter visibility through the argument that subclutter visibility must be restricted to the point where spurious responses will not be introduced by this sensitivity. Thus

$$R_{max} \ll \left| \sin \frac{\pi \, \Delta f_s}{(PRF)} \right|^{-1} \tag{106}$$

where

R_{max} = maximum permissible subclutter visibility.

Or, solving for the allowable error (Δf_s) in compensation for a given maximum subclutter visibility,

$$\Delta f_s \ll \frac{(PRF)}{\pi} \sin^{-1} \frac{1}{R_{max}} . \tag{107}$$

But, in the case of a practical MTI system, R_{max} will be large enough so that,

$$\sin^{-1} \frac{1}{R_{max}} \cong \frac{1}{R_{max}} .$$

Thus, equation (107) becomes

$$\Delta f_s \ll \frac{(PRF)}{\pi R_{max}} . \tag{107.1}$$

During the course of the above discussion the coho has been assumed to be at radio frequency. The frequency and phase shifts introduced into echo signals at radio frequency by the doppler effect are preserved unchanged through frequency conversion. Thus, the relations developed hold identically whether coho is at radio frequency or at intermediate frequency.

System Limitation

Unfortunately, the use of coho shift for velocity compensation cannot provide complete compensation. Since all stationary targets which are within the radar antenna beam at a given time do not appear to be moving at the same relative speed, the method has a fundamental limitation.

Consider three stationary targets off the beam of a moving ship, one on 090° relative and the other two on 090° $\pm \theta_e/2$ relative.[4] The antenna is pointed on 090° relative. It

---

[4] θ_e, the effective clutter beamwidth of the radar antenna, is the width of the antenna beam at the points at which clutter just reaches limit level in the receiver. Thus, it is dependent not only on the width of the antenna beam, but also on the slope of the skirts of the antenna beam, the limit level of the receiver, and the clutter strength. For 30-db limit level, it will equal θ_b for 36-db clutter and will, for ordinary antenna patterns, be about 2.0 θ_b for 80-db clutter.

will be obvious that, since the ship's motion is exactly perpendicular to the radius line to the target on 090° relative, there will be no motion with respect to this target and it will be cancelled as a stationary target. However, since both the other targets are on bearings $\theta_e/2$ degrees off the normal to the ship's course, the ship will have a relative velocity with respect to them (toward one and away from the other) which can be shown to be

$$\nu_s^{(r)} = \nu_s \sin \frac{\theta_e}{2},$$

where

$\nu_s^{(r)}$ = ship's relative velocity,

ν_s = ship's true speed,

θ_e = effective clutter beamwidth of antenna[5]

Obviously this velocity cannot be compensated for since it is of opposite sign on the two sides of the beam.

If again we take the fundamental equation for the relative sensitivity versus target radial velocity for an MTI system,

$$S_r = \left| \sin \frac{2\pi \, \nu_t^{(r)} f_o}{(PRF) \; c} \right|, \tag{14}$$

where

S_r = relative sensitivity,

$\nu_t^{(r)}$ = target radial velocity,

f_o = transmitted frequency,

c = velocity of light,

we may substitute the target's radial velocity relative to the ship ($\nu_s^{(r)}$) and find the sensitivity of the system to these two targets on the edge of the beam. Thus,

$$S_r = \left| \sin \frac{2\pi f_o \, \nu_s \sin \frac{\theta_e}{2}}{(PRF) \; c} \right|,$$

or, in terms of the speed at which the first null in the system response occurs ($V_{null}^{(1)}$),

$$S_r = \left| \sin \frac{\pi \, \nu_s \sin \frac{\theta_e}{2}}{V_{null}^{(1)}} \right|, \tag{27a}$$ [6]

---

[5] See footnote 4 page 6.

[6] See footnote 2 page 2.

where

$$V^{(n)}_{null} = \frac{n\,(PRF)\,c}{2 f_o} \tag{13}$$

with

$$n = 1.$$

Thus, the system will, even though perfectly compensated for targets at the center of the beam, have a relative sensitivity of this value to targets at the edge of the beam. This condition is worst when the antenna is pointed dead abeam, so that if the subclutter visibility of the MTI system is to be restricted to a value such that it will be satisfactory for all antenna bearings, it must be limited to

$$R_{max} \ll \left| \sin \frac{\pi \nu_s \sin \frac{\theta_e}{2}}{V^{(1)}_{null}} \right|^{-1}, \tag{28a}$$

where

$$R_{max} = \text{maximum permissible subclutter visibility.}$$

This equation may generally be simplified slightly since θ_e will be small enough that

$$\sin \frac{\theta_e}{2 \times 57} \simeq \frac{\theta_e}{2 \times 57}.^{7}$$

Thus, equation 28a becomes,

$$R_{max} \ll \left| \sin \frac{\pi \nu_s \theta_e}{114\, V^{(1)}_{null}} \right|^{-1} \tag{28.1a}$$

VELOCITY COMPENSATOR CIRCUIT AND ITS OPERATION

The velocity compensator (shown in block diagram form in Figure 1) can be divided into five parts. The first, the compensation Control Unit, receives information as to relative antenna-bearing (θ_r) and ship's speed (ν_S), and from these, develops two d-c voltages

$$\begin{cases} A_{1.1} = k_1\, \nu_S \cos \theta_r \\ A_{1.2} = -k_1\, \nu_S \cos \theta_r \end{cases}$$

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[7] Note that the factor 1/57 converts θ_e to radians.

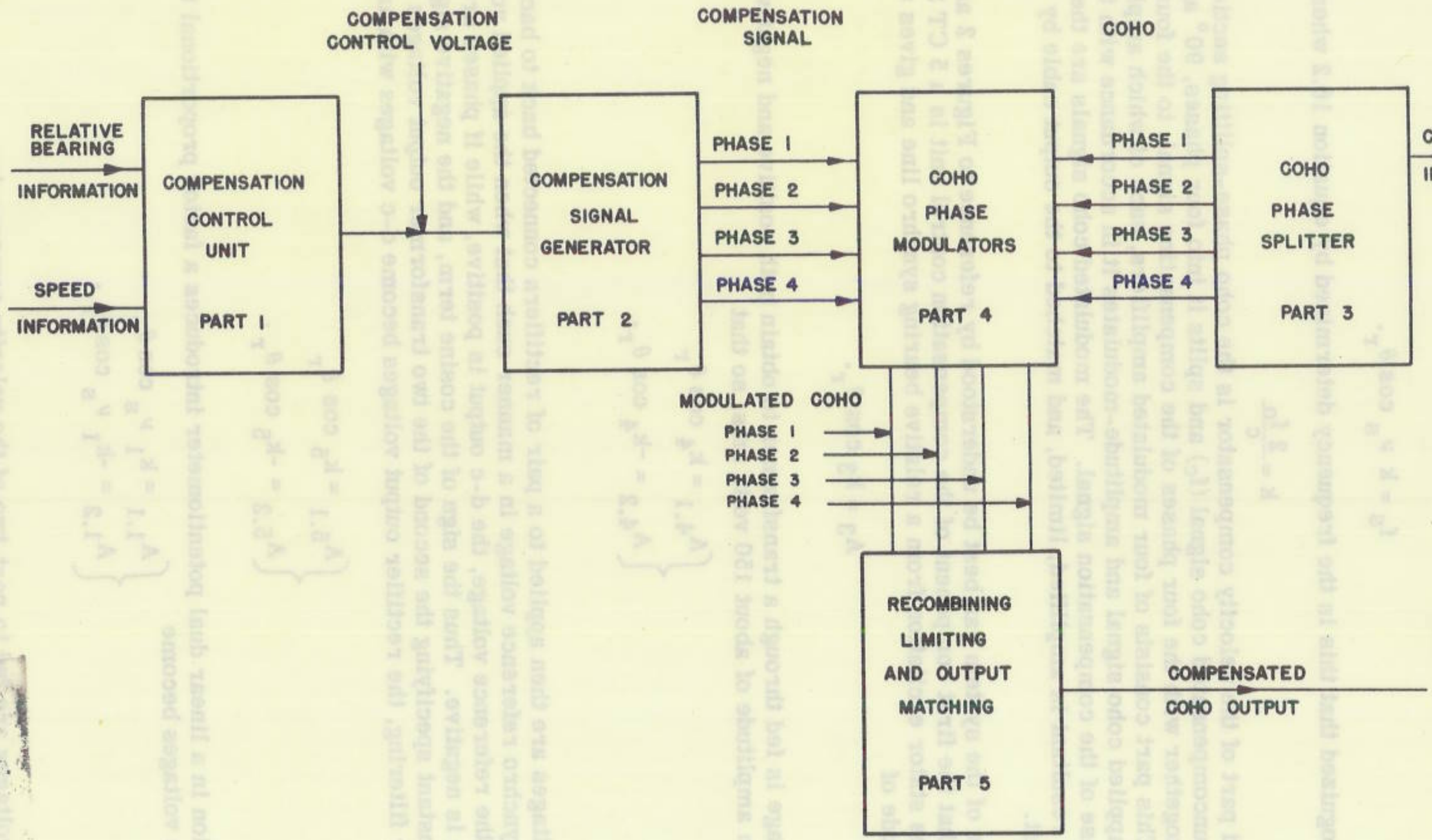

Fig. 1 - Functional Block Diagram Velocity Compensator for MTI

These two voltages are fed to the second part of the system which develops four phases (90 degrees apart) of the compensating frequency for the coho. Thus

$$f_s = k\, \nu_s \cos \theta_r.$$

It will be recognized that this is the frequency determined by equation 16.2 where

$$k = \frac{2\, f_0}{c}$$

The third part of the velocity compensator is the coho phase-splitting section which receives the uncompensated coho signal (f_c) and splits it into four phases, 90° apart, to be supplied, together with the four phases of the compensating signal, to the fourth part of the unit. This part consists of four modulated amplifiers, each of which amplifies a phase of the applied coho signal and amplitude-modulates it in accordance with the appropriate phase of the compensation signal. The modulated coho signals are then recombined and the resultant is amplified, limited, and matched to the output cable by the last part of the unit.

Operation of the system can best be understood by reference to Figures 2 and 3. It will be seen that the first component of the compensation control unit is a 5 CT Synchro which receives stator excitation from a relative bearing synchro line and gives a rotor output amplitude of

$$A_3 = k_3 \cos \theta_r.$$

This voltage is fed through a transformer to obtain both positive and negative polarity at a maximum amplitude of about 150 volts rms; so that

$$\begin{cases} A_{4.1} = k_4 \cos \theta_r \\ A_{4.2} = -k_4 \cos \theta_r. \end{cases}$$

These voltages are then applied to a pair of rectifiers connected back to back, and gated by the synchro reference voltage in a manner such that when the applied voltage is in phase with the reference voltage, the d-c output is positive, while if phases are opposite, the d-c output is negative. Thus the sign of the cosine term, and the negative sign which is part of the constant specifying the second of the two transformer output voltages are preserved. After filtering, the rectifier output voltages become d-c voltages with amplitudes,

$$\begin{cases} A_{5.1} = k_5 \cos \theta_r \\ A_{5.2} = -k_5 \cos \theta_r. \end{cases}$$

Multiplication in a linear dual potentiometer introduces a factor proportional to ship's speed, and the voltages become

$$\begin{cases} A_{1.1} = k_1\, \nu_s \cos \theta_r \\ A_{1.2} = -k_1\, \nu_s \cos \theta_r. \end{cases}$$

These output voltages are fed to part two of the velocity compensator.

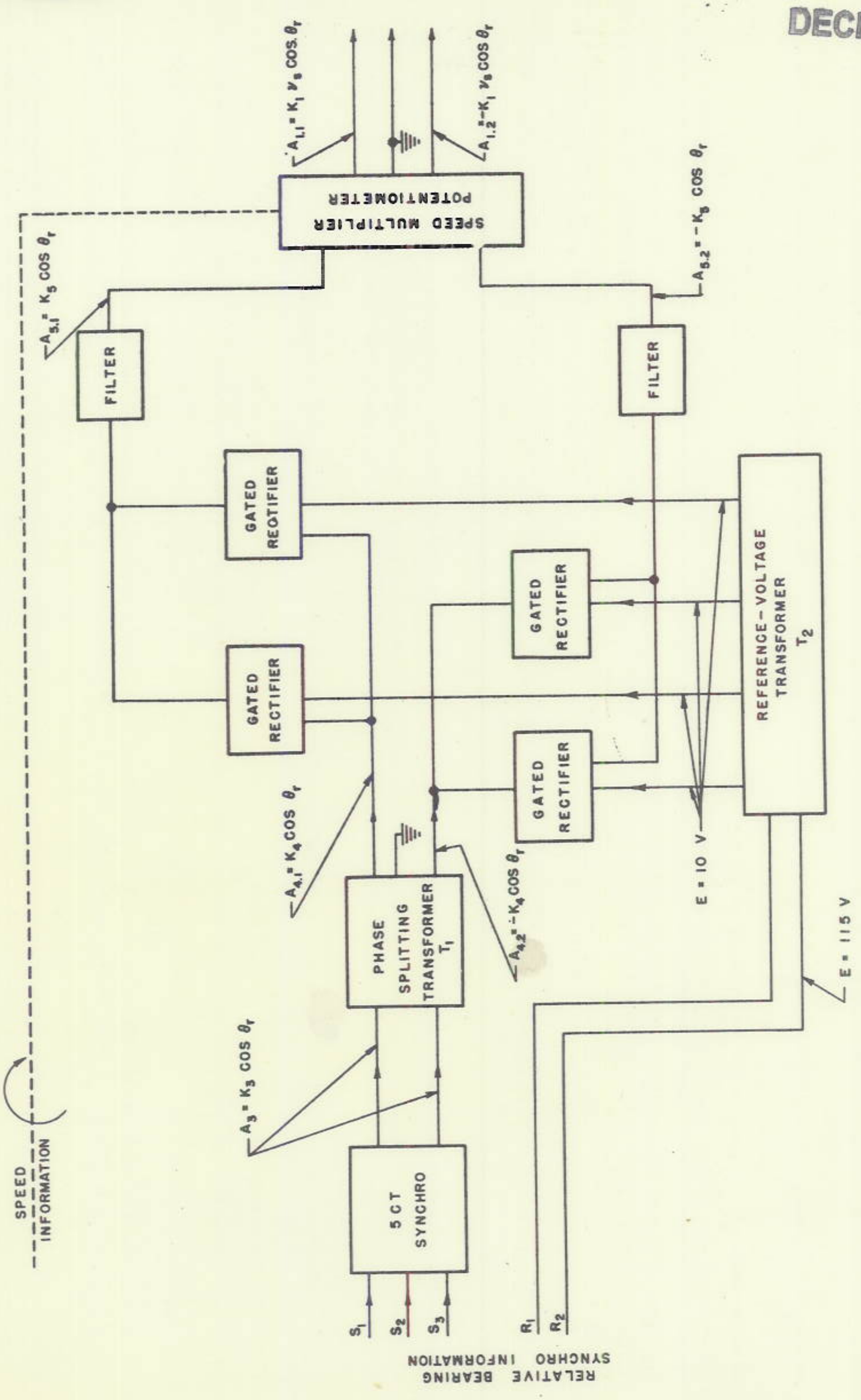

Fig. 2 - Detail Block Diagram Compensation Control Unit

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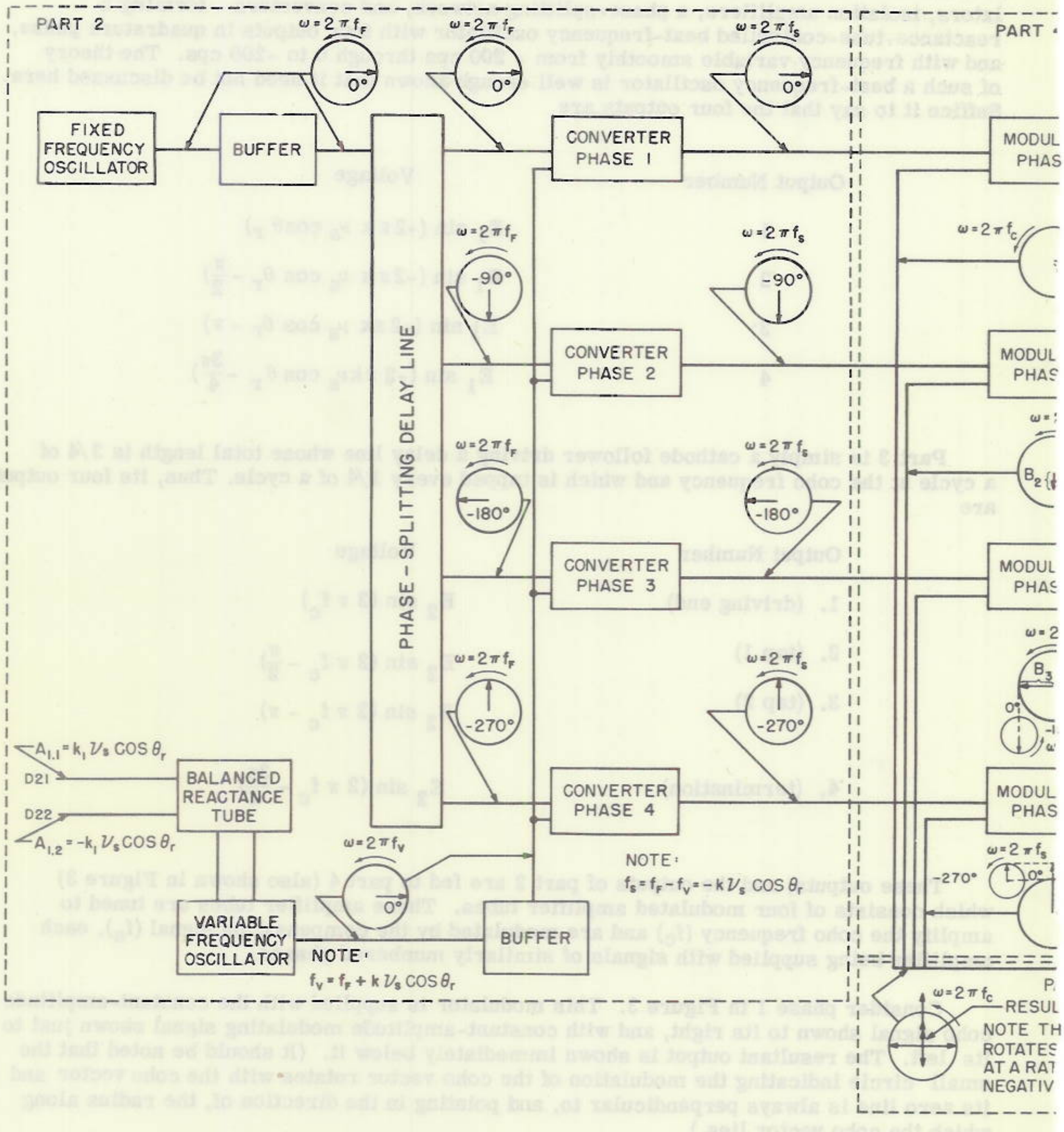

Fig. 3 - Vector Diagram - V

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Part 2 is shown in the detail block diagram, and in the vector diagram Figure 3. It will be seen that this part is the compensation signal generator consisting of two oscillators, isolation amplifiers, a phase-splitting network, and converters - forming a reactance-tube-controlled beat-frequency oscillator with four outputs in quadrature phase, and with frequency variable smoothly from + 200 cps through 0 to -200 cps. The theory of such a beat-frequency oscillator is well enough known that it need not be discussed here. Suffice it to say that the four outputs are

Output Number	Voltage
1	$E_1 \sin(-2\pi k\, \nu_S \cos\theta_r)$
2	$E_1 \sin(-2\pi k\, \nu_S \cos\theta_r - \frac{\pi}{2})$
3	$E_1 \sin(-2\pi k\, \nu_S \cos\theta_r - \pi)$
4	$E_1 \sin(-2\pi k \nu_S \cos\theta_r - \frac{3\pi}{4})$

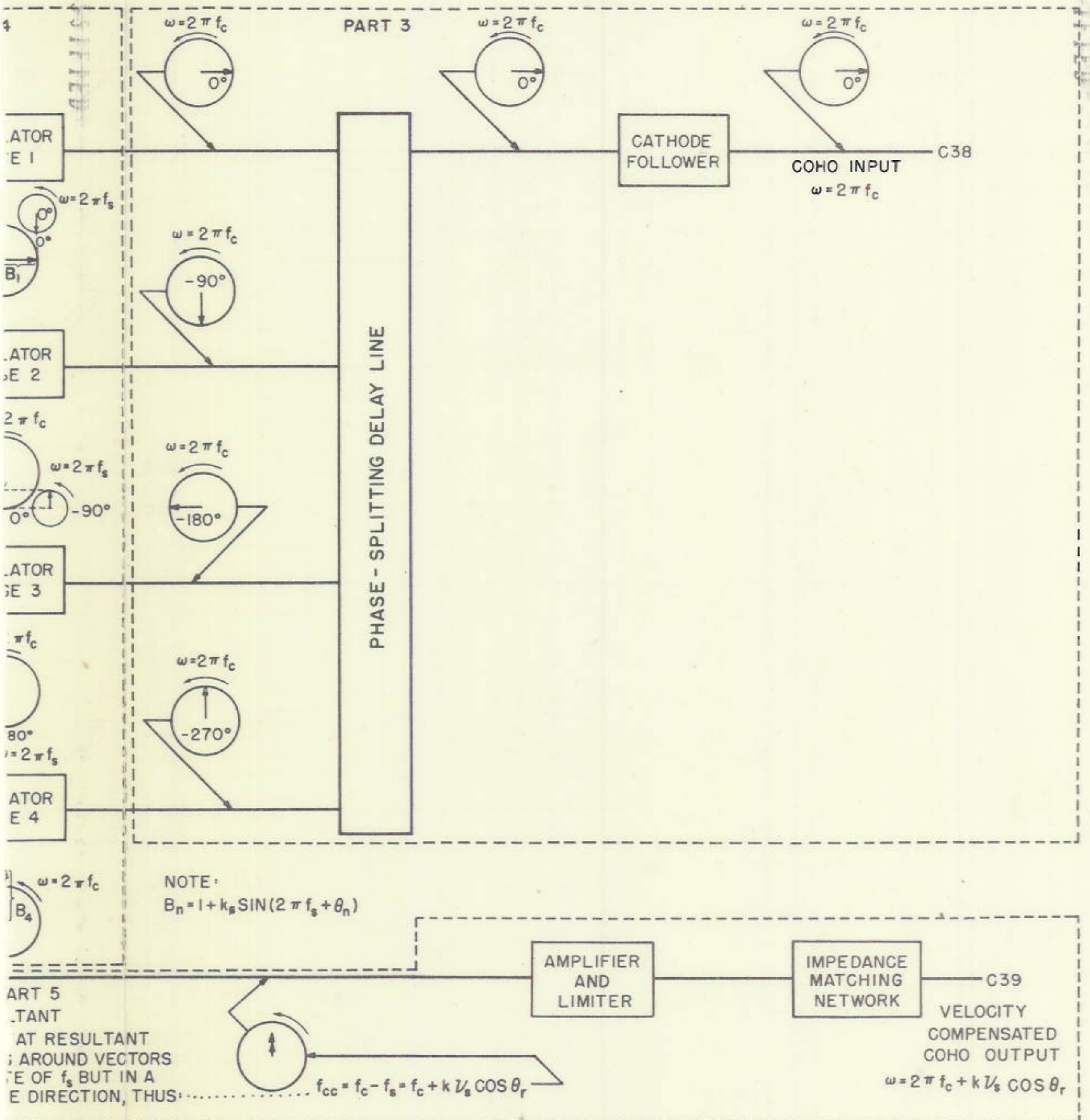
Part 3 is simply a cathode follower driving a delay line whose total length is 3/4 of a cycle at the coho frequency and which is tapped every 1/4 of a cycle. Thus, its four outputs are

Output Number	Voltage
1. (driving end)	$E_2 \sin(2\pi f_c)$
2. (tap 1)	$E_2 \sin(2\pi f_c - \frac{\pi}{2})$
3. (tap 2)	$E_2 \sin(2\pi f_c - \pi)$
4. (termination)	$E_2 \sin(2\pi f_c - \frac{3\pi}{4})$

These outputs, and the outputs of part 2 are fed to part 4 (also shown in Figure 3) which consists of four modulated amplifier tubes. These amplifier tubes are tuned to amplify the coho frequency (f_c) and are modulated by the compensation signal (f_S), each amplifier being supplied with signals of similarly numbered phases.

Consider phase 1 in Figure 3. This modulator is supplied with the constant-amplitude coho signal shown to its right, and with constant-amplitude modulating signal shown just to its left. The resultant output is shown immediately below it. (It should be noted that the small circle indicating the modulation of the coho vector rotates with the coho vector and its zero line is always perpendicular to, and pointing in the direction of, the radius along which the coho vector lies.)

In phase 1, the modulation vector is at 0° and causes no change in amplitude of phase 1 of the coho. In phase 2, however, the modulation vector is at -90° and thus reduces the amplitude of phase 2 of the coho. Similarly in phase 3 the coho amplitude is unchanged but in phase 4 it is increased. [redacted]



elocity Compensator for MTI

A further study of this diagram will reveal that as phase of the modulating signal rotates in the positive direction, phase 1 of the modulated coho, will increase in amplitude, phase 2 will increase, and phases 3 and 4 will decrease until, after 90° of such rotation, phase 1 will be maximum amplitude, phase 2 will be unaffected, phase 3 will be minimum amplitude, and phase 4 will be unaffected.

Finally, these four vectors are added together in part five to give a resultant again as shown in Figure 3. It will be noted that as shown, the resultant is in the direction of phase 4 and that as the modulation phase increases in the positive direction a given amount, the resultant rotates in the negative direction (from phase 4 to phase 1 to phase 2 etc.) by the same amount. Thus, the resultant is of the form

$$f_{cc} = f_c - f_s.$$

but

$$f_s = -k\ \nu_s \cos \theta_r;$$

so

$$f_{cc} = f_c + k\ \nu_s \cos \theta_r.$$

It will be noted that this is the desired shifted coho frequency provided that

$$k = \frac{2 f_o}{c}.$$

This constant (k) may be set to the correct valve by adjusting the amount of drive supplied by the compensation control unit by means of a divider at the output of the filters.

As a final step in the processing of this signal, the resultant is amplified, limited to insure constant amplitude, and then delivered through an impedance-matching transformer to the output terminal.

VELOCITY COMPENSATION FOR SR-3 AND SPS-6 RADARS

System Parameters

The parameters of the SR-3 and SPS-6 Systems with which this work is concerned are as follows:

$$f_o = 1300 \pm 50 \text{ Mc}$$

$$PRF = 500 \text{ cps}$$

$$\theta_b = 3.1^\circ$$

$$\nu_s = 40 \text{ knots } (46.0 \text{ mph})$$

$$V_{null}^{(1)} = 112 \text{ knots } (129 \text{ mph})$$

$$R_{desired} = 31.6 \text{ (30 db)}$$

$$I\,F = 30 \text{ Mc}$$

Substituting in equation 16.2 we find that

$$f_s = \frac{2 \times 46.0 \cos \theta_r}{1.86 \times 10^5 \times 3.6 \times 10^3} \, 13 \times 10^8$$

$$= 179 \cos \theta_r \text{ cycles/sec.}$$

Thus, the velocity compensator must be capable of shifting the 30-Mc coho frequency from +179 cps through 0 to -179 cps.

Substituting the appropriate parameters in equation 107.1,

$$\Delta f_s \ll \frac{500}{\pi \times 31.6} = 5 \text{ cps.}$$

Thus, if error in compensation is not to limit subclutter visibility, compensation must be accurate to within 5 cps.

Substituting the appropriate parameters in equation 28.1,

$$R_{max} \ll \left| \sin \frac{\pi \times 46.0 \times 3.1}{114 \times 129} \right|^{-1} = 32.2$$

Thus, subclutter visibility will not be limited by this factor for clutter levels below 36 db. For higher clutter levels (where $\theta_e > \theta_b$) this will be the limiting factor.

Circuit

The velocity compensator for the SR-3 and SPS-6 radars is shown in Figures 4 to 7. Figure 4 shows the compensation control unit which is mounted in a separate box on top of the main MTI conversion unit. Figure 5 shows unit number one of the MTI conversion unit. This unit consists of the velocity compensator, a zero-adjust scope and all associated power supplies, as well as the master control for the entire conversion unit. Figure 6 shows an underside view, and Figure 7 shows a topside view of the 16-tube subchassis containing the velocity compensation circuits.

Consider first the compensation control unit. Its circuit is shown in Diagram 1.[8] Relative-bearing synchro information is supplied to the unit over lines 57, 58, and 59; and 96 and 97. Lines 57, 58, and 59 are connected to a 5 CT synchro whose rotor is so positioned as to give a 60-cycle output voltage whose amplitude is

$$A_3 = k_3 \cos \theta_r$$

This output voltage is stepped up and converted to balanced-to-ground connection by transformer T_1. Thus, applied to V-701 we have

$$A_{4.1} = k_4 \cos \theta_r$$

and applied to V-702,

$$A_{4.2} = -k_4 \cos \theta_r \, .$$

[8] All Diagrams located at end of report.

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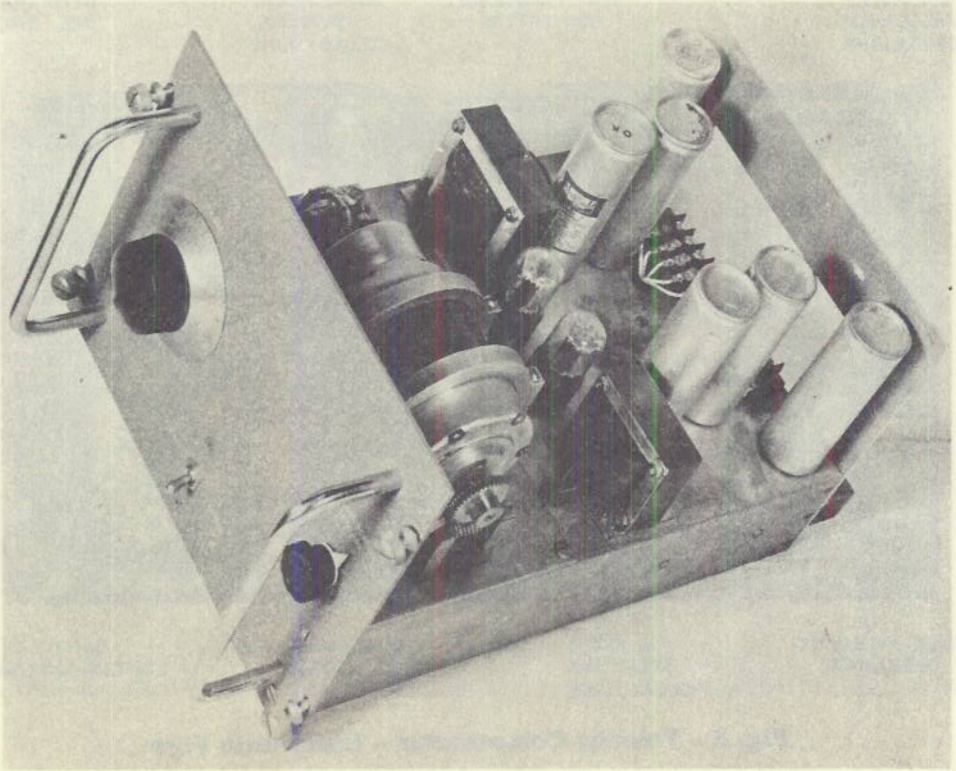

Fig. 4 - Compensation Control Unit MTI Conversion Unit
for SR-3 and SPS-6 Radars

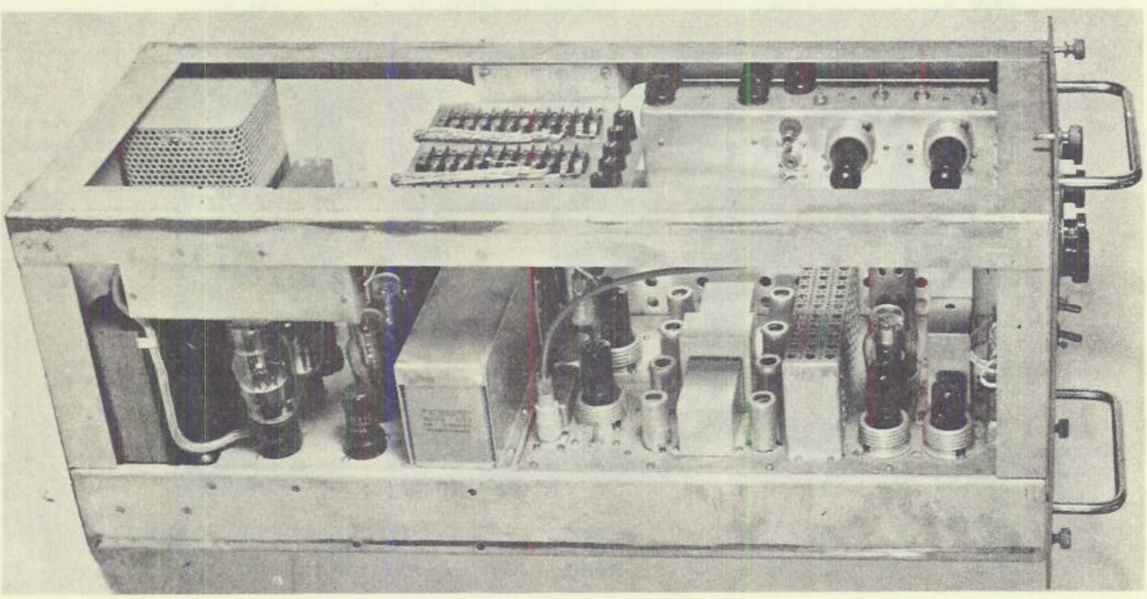

Fig. 5 - Velocity Compensator Unit MTI Conversion Unit
for SR-3 and SPS-6 Radars

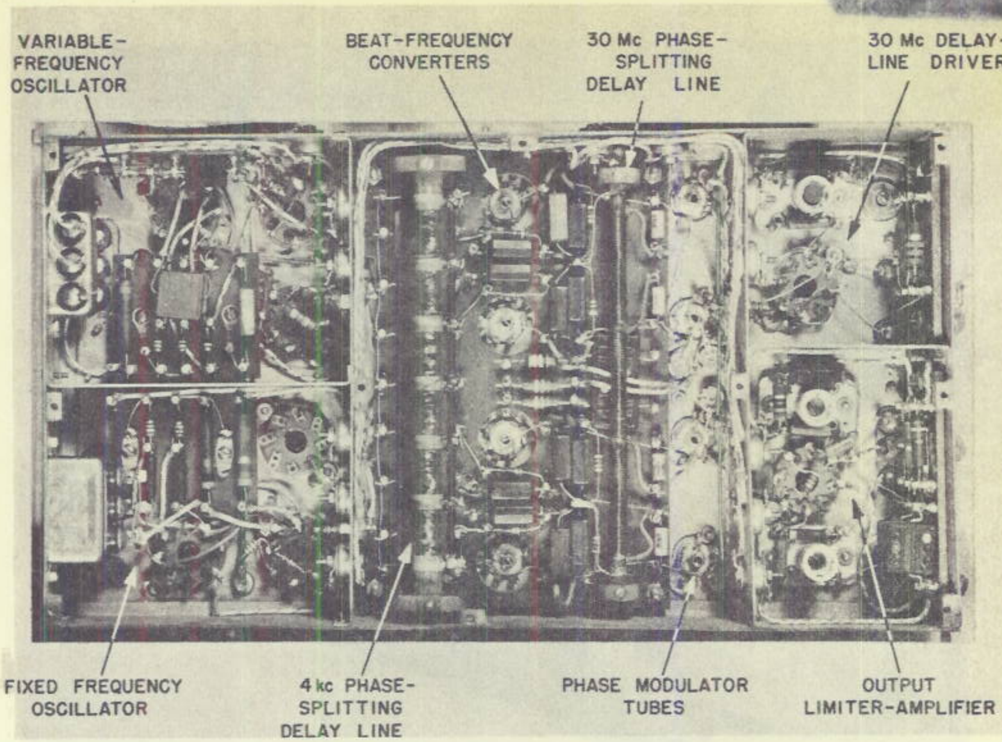

Fig. 6 - Velocity Compensator - Underneath View

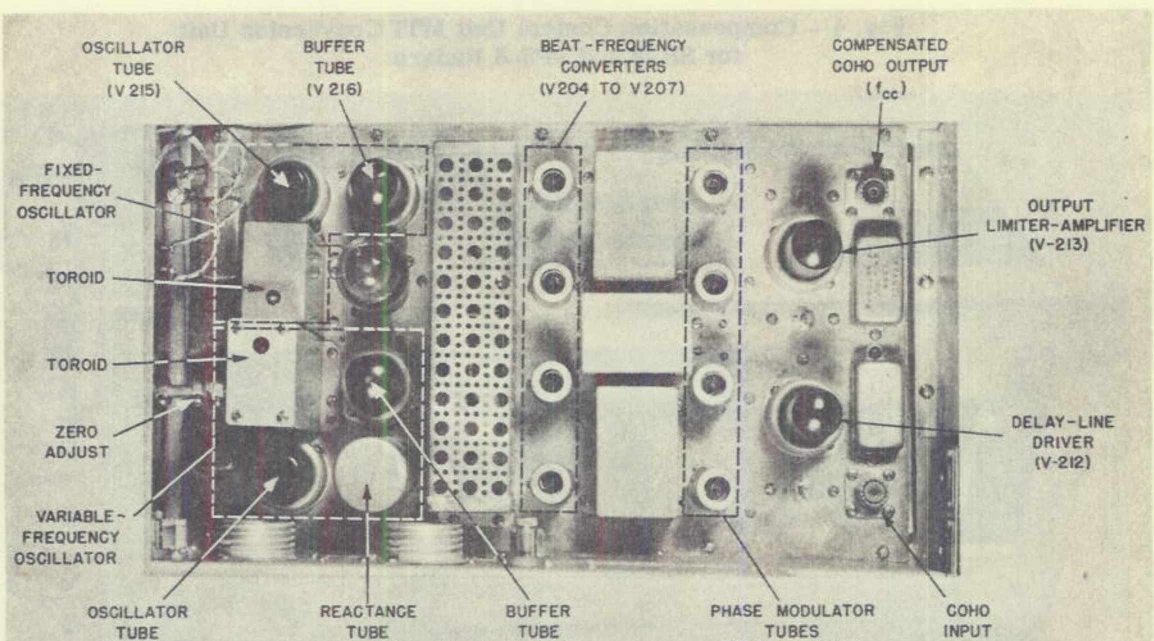

Fig. 7 - Velocity Compensator - Closeup of Compensator Subchassis

Applied to the grids of both V-701 and V-702 we have about 10 volts of 60-cycle reference voltage derived from the synchro excitation line (lines 96 and 97) by transformer T_2.

It will be clear that, since these tubes go to a very low impedance when conducting, the output voltage on each of the two lines will closely approximate the peak voltage of the applied wave; being of the form,

$$A_5 = \left| k_5 \cos \theta_r \right|.$$

But all grids are driven in phase, and the gated rectifiers are connected back to back; so, when the phases of the applied voltages are as shown, the upper output line will be positive (V-701-A conducting) and the lower output line will be negative (V-702-B conducting). Thus, the minus sign on the lower line is retained.

Further examination of this connection also reveals that, if the polarity of T_1 reverses, conduction will switch from V-701-A to V-701-B, thus reversing the polarity of this output, and from V-702-B to V-702-A, also reversing the polarity of this line. Obviously then, sign is preserved through the rectification and the absolute value signs may be removed, making the outputs

$$A_{5.1} = k_5 \cos \theta_r,$$

and

$$A_{5.2} = -k_5 \cos \theta_r.$$

These two voltages are filtered to obtain pure dc and multiplied, in ganged linear potentiometers by a factor proportional to ship's speed, to give the final outputs

$$A_{1.1} = k_1 \nu_S \cos \theta_r$$

and

$$A_{1.2} = -k_1 \nu_S \cos \theta_r.$$

These two outputs are fed over lines D21 and D22 to the velocity compensator.

The velocity compensator is shown in Diagram 2. At the extreme left of this diagram may be seen the two beating oscillators (V-202 and V-215) which in the present application are operated at 4 kc. This frequency, chosen because it is high enough to allow a reactance tube to vary the frequency of the variable oscillator the required ±180 cps, is still low enough to allow the better-than-5-cps stability to be attained. It will be noted that both oscillators are identical (with the exception of the reactance tube) and employ a 6SC7 tube in a balanced circuit and a high-Q toroid tank circuit.[9] The use of these toroids proved to be mandatory in this application since the variable-frequency oscillator must be able to pass smoothly through zero beat with the fixed-frequency oscillator without tending to lock in with it, and since they were the only coils in which direct mutual coupling between coils did not cause locking-in when the variable oscillator was within 5 to 10 cps of the fixed oscillator. The reactance tube (V-201), also balanced, is a 6SN7 tube and has proved capable of easily providing the necessary frequency shift.

It should be noted here, that in the system constructed at this Laboratory using regulated plate and heater power, and with the circuit shown, no troubles whatsoever have been experienced with oscillator stability. After a five-minute warm-up period, the

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[9] NRL Coil Winding Shop Specification No. 3477 - Q >100.

oscillators may be adjusted to zero beat and will remain within about 2 cycles thereof for the entire day with no tendency to lock in.

The output of the fixed-frequency oscillator is fed through a buffer tube (V-216) to a phase-splitting delay line of the lumped-constant M-derived low-pass-filter type. The four outputs of this delay line are fed to resistance-capacitance L-section filters to allow amplitude and phase correction for delay-line losses and inaccuracies.

The output of the variable-frequency oscillator is fed through a buffer stage (V-203) to transformer T_3. This transformer (NRL #3500) consists of an iron core with five, spaced, universal-wound coils on its center leg. The center coil is the primary and the other four windings are the four secondaries, each of which is connected in series with one of the delay-line outputs, and thence to one of the four converter tubes (V-204 to V-207 inc.)

It is important to note here that the variable-frequency oscillator signal supplied to these converter tubes is of a level 2 or 3 times as great as the fixed-frequency signal. This tends to suppress any change in converter output as frequency is varied. The outputs of these four converters are fed through pi-section low-pass filters and, after filtering, are the four phases of the compensation signal (f_s) which are applied, along with the 30-Mc coho signal, to the four modulator tubes (V-208 to V-211 inclusive).

Coho signal is brought into the unit over cable C38 and matched to the phase-splitting delay line by a cathode follower (V-212). This delay line, a distributed wound line (shown in Figure 6) supplies the required four phases of the coho signal.

After these four phases of the coho signal (f_o) have been modulated by the appropriate phases of the compensation signal (f_s), they are recombined in the common plate connection of the modulator tubes. The signal at this point is then the resultant shown in Figure 3. As will be seen it has a frequency of,

$$f_{cc} = f_c - f_s = f_c + k\, \nu_s \cos \theta_T$$

and is the desired compensated coho signal.

Before leaving the unit this signal is amplified and limited by V-213 to remove any amplitude variations which might result from circuit imperfections or differences in modulator tubes. After this limiting, the signal is matched in a pi-section network to the 50-ohm output cable (C39).

Auxiliaries

Power Supplies -- The power supplies for the velocity compensator are shown pictorially in Figure 5 and diagramatically in Diagram 3.

It will be noted that all power (including heater power) to the velocity compensator is regulated; the plate power by means of an electronic regulator consisting of tubes V-221, V-222, and V-223; and the heater power by means of the Sola regulating transformer visible in the lower right hand corner of Figure 5. This regulation of all power, including heaters, is not essential to maintain accuracy. The use of balanced circuits and high-Q tank coils in the oscillators gives excellent stability, and the use of similar circuits (except for the reactance tube) minimizes the possibility of their drifting different amounts or in different directions. The use of regulation of all power is, however, good insurance against possible troubles due to the bad line-voltage fluctuations sometimes encountered.

Zero-Adjust Scope -- Also included in the velocity compensation unit, is a zero-adjust scope, the edge of which may be seen immediately above the velocity compensator in Figure 5. Its circuit is included in Diagram 3.

This scope consists of a 2AP1 cathode-ray tube (V-219) and two deflection dual-frequency amplifiers (V-217 and V-218) so arranged as to amplify a video signal fed in at TP-1 or TP-2, or, to amplify the 30-Mc coho signal when connected in lines C38 and C39. Ordinarily, the scope will be connected in the latter fashion and will be used to check and adjust the zero of the velocity compensator. It may, however, be used for checking the low-frequency circuits of the velocity compensator (or other units) by plugging test leads in TP-1 and TP-2.

PERFORMANCE

The performance of the velocity compensator is shown in Figure 8. It will be seen that the accuracy of compensation is such that 30-db subclutter visibility may be maintained up to about 33 knots and that at 40 knots a subclutter visibility of about 25-db may be realized.

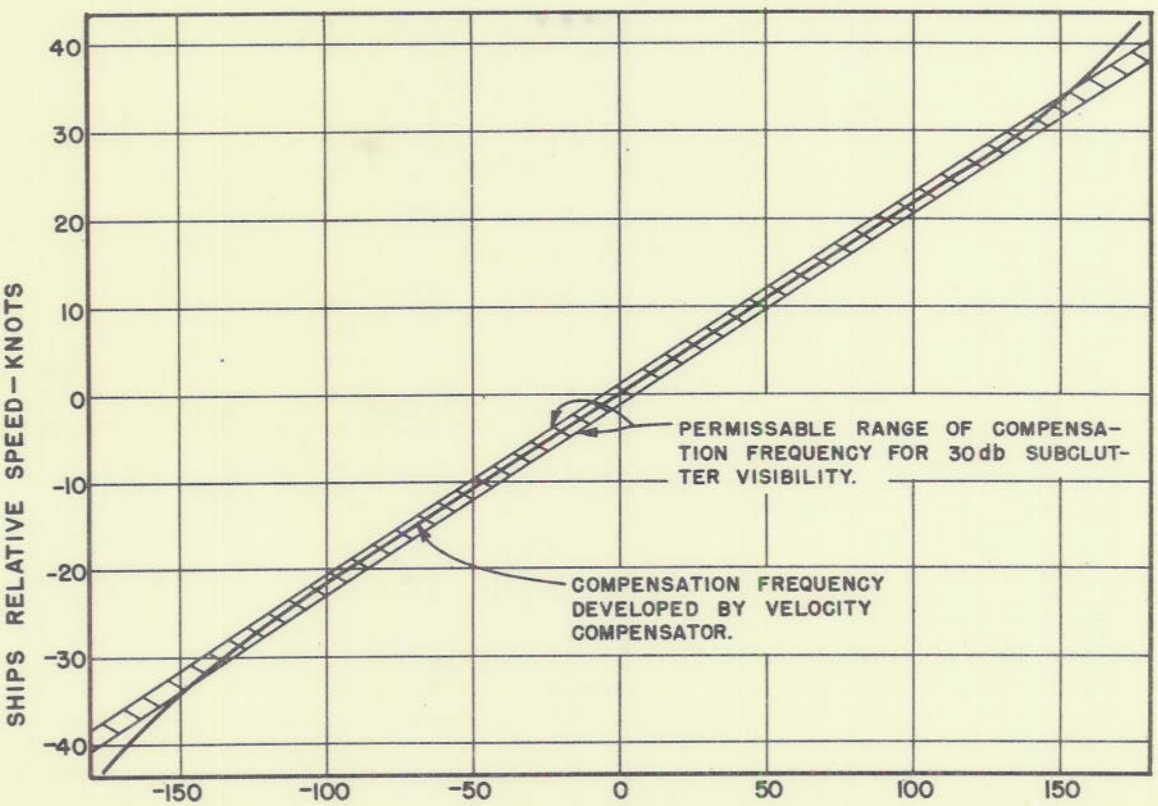

Fig. 8 - Compensation Frequency - CPS

The reliability and stability of this unit are excellent. After about a five minute warm-up the unit may be zero-adjusted, and this adjustment will be maintained throughout the entire day with sufficient accuracy to not limit the 30-db subclutter visibility.

Performance tests of this unit in its associated system are not as yet completed and so cannot be reported here. (They will be reported in a separate report which will cover the test of the entire SR-3 and SPS-6 MTI Conversion Unit.) Preliminary operations with the system do, however, indicate that performance will be satisfactory, and no difficulties are expected.

APPLICATION TO OTHER SYSTEMS

The present compensator was designed for use with the SR-3 and SPS-6 systems; however, with appropriate choice of parameters, it could have been designed for use with almost any system requiring velocity compensation by coho shift.

Also, it will be apparent that, where weight and space are of primary importance, the system could be somewhat simplified by using a 3-phase system instead of a 4-phase system. Such simplification would, however, be made at the expense of making some of the components more critical.

* * *

APPENDIX 1

Useful Equations

The following equations may be useful in the design of a coho shift velocity compensator for an MTI system:

Coho frequency shift necessary for velocity compensation.

$$f_s \cong \frac{2\,\nu_s\,f_o}{c}\cos\theta_r \qquad (16.1a)^*$$

or,

$$f_s \cong \frac{\nu_s\,(PRF)}{V_{null}^{(1)}}\cos\theta_r\,. \qquad (16.2)$$

Allowable error in coho frequency shift.

$$\Delta f_s \ll \frac{(PRF)}{\pi R_{max}} \qquad (107.1)$$

Limit on subclutter visibility due to velocity compensation by coho shift.

$$R_{max} \ll \left|\sin\frac{\pi\,\nu_s\,\theta_e}{114\,V_{null}^{(1)}}\right|^{-1} \qquad (28a)$$

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* $c = 6.7 \times 10^8$ mph

* * *

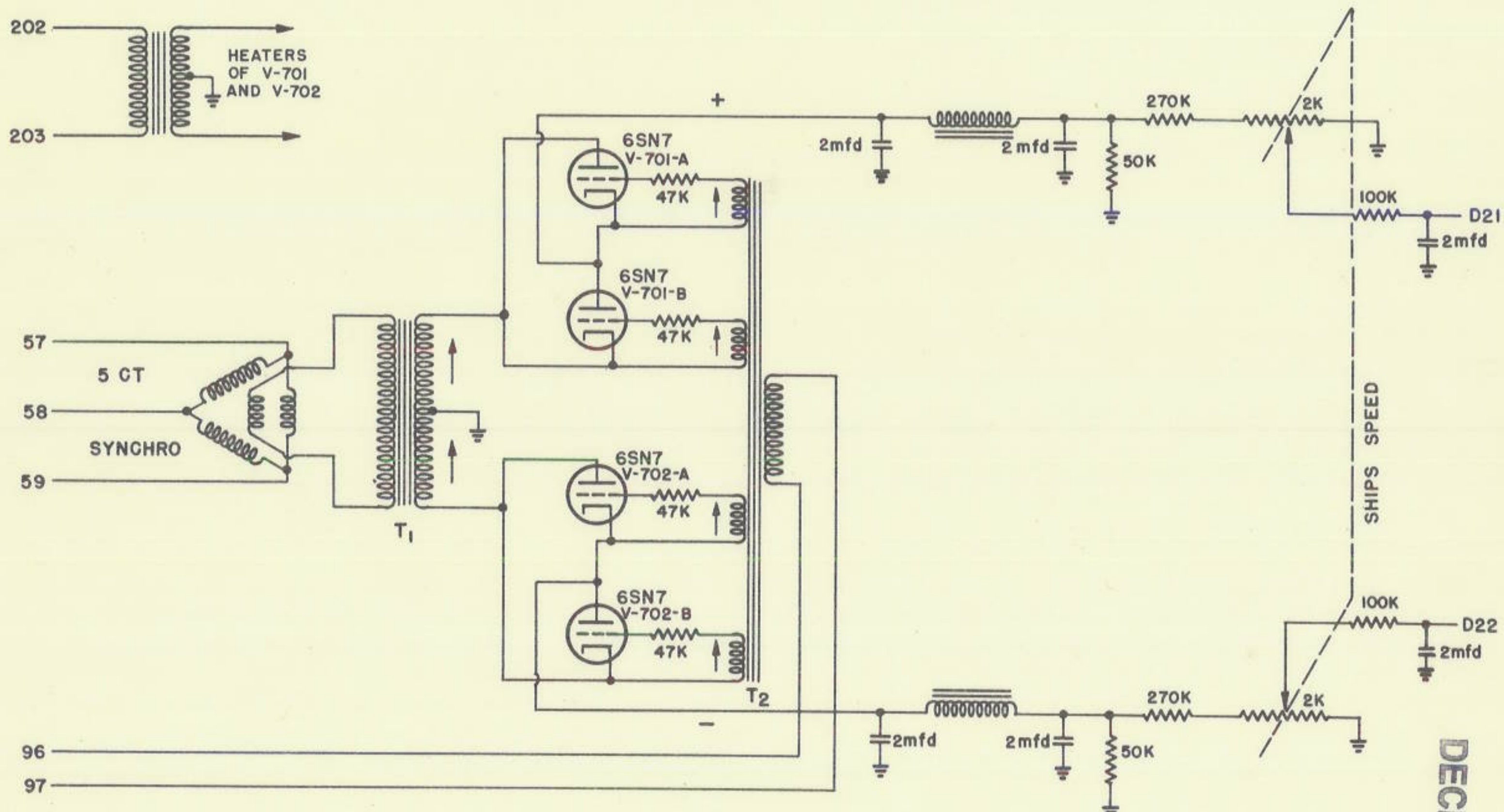

DIAGRAM 1
Circuit Diagram
Compensation Control Unit

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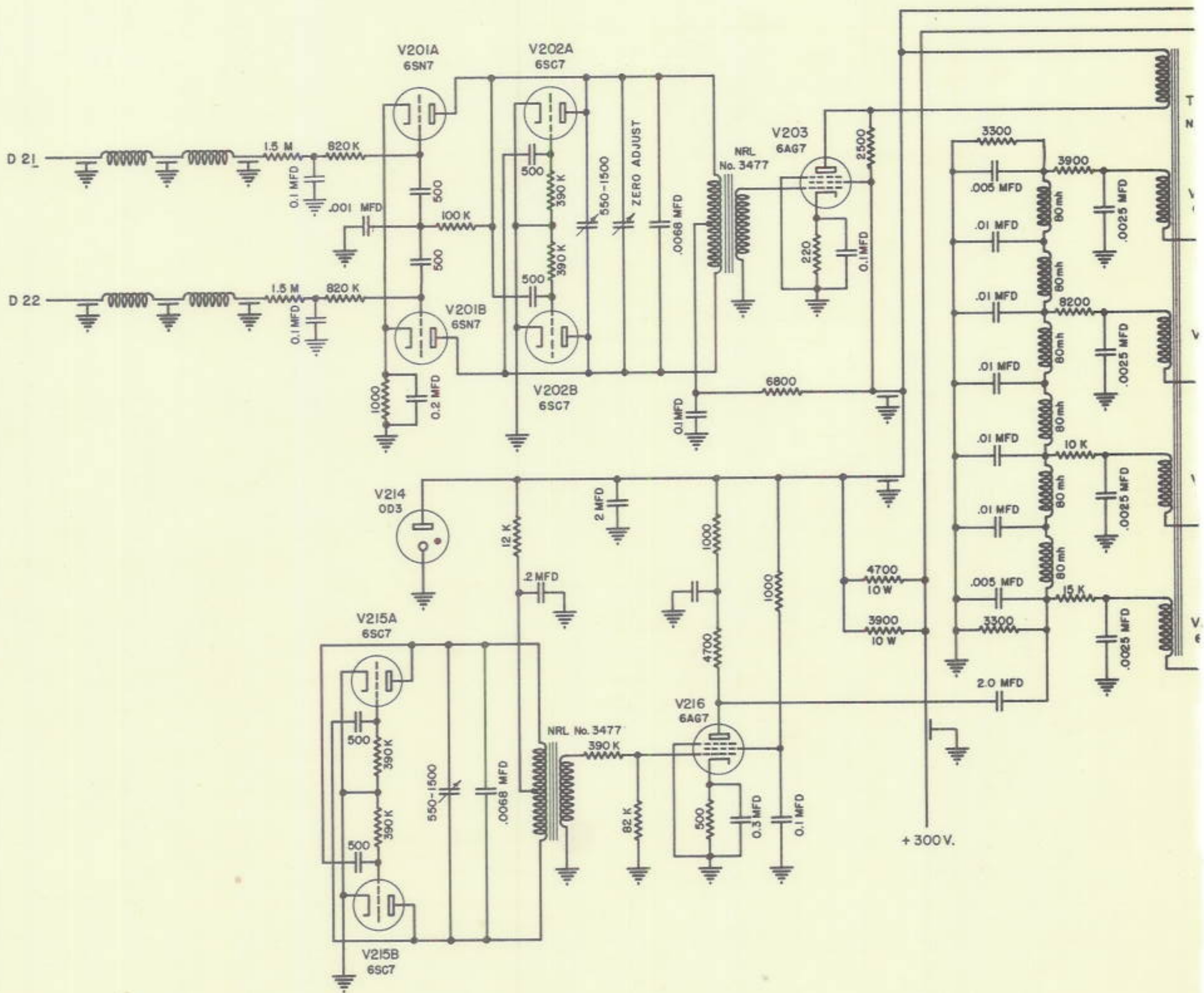

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Diagram 2 - Circuit Diagram - Velocity Comp

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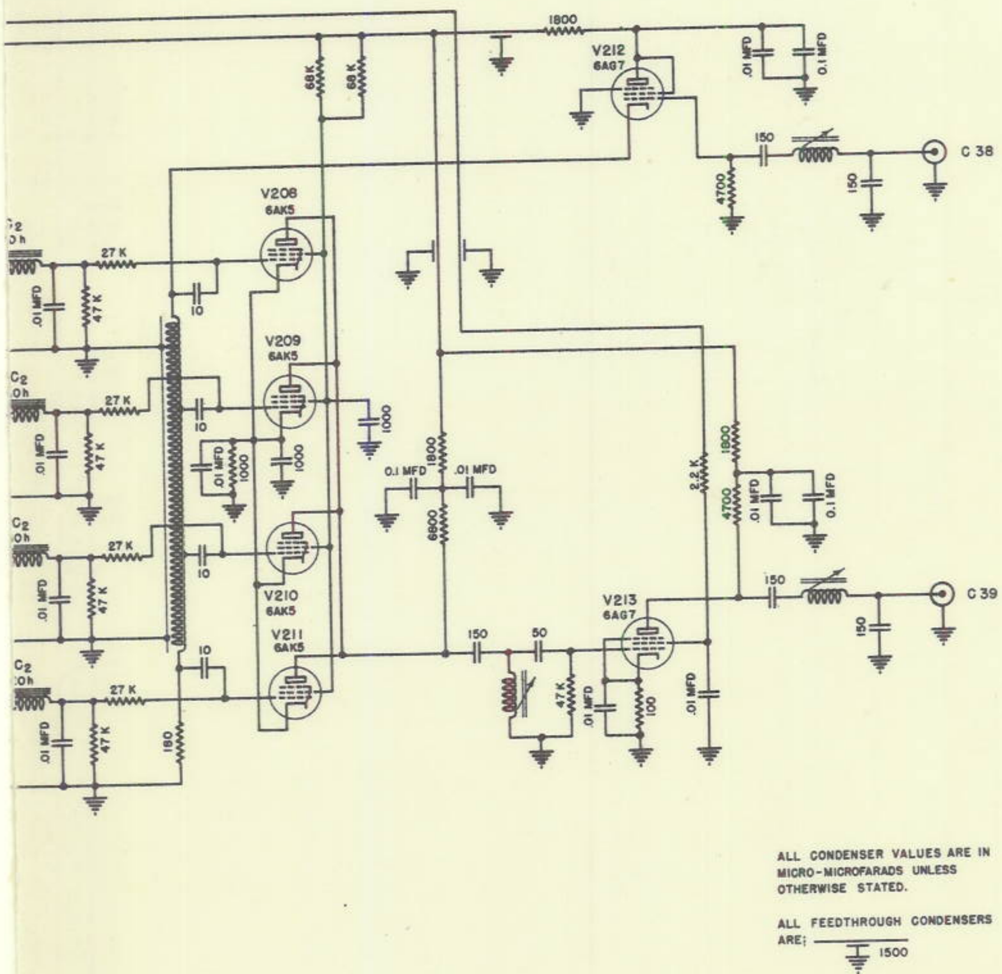
1800
V212
6AG7
.01 MFD
0.1 MFD
68K
68K
150
C 38
4700
150
V208
6AK5
27 K
.01 MFD
47 K
10
V209
6AK5
1000
1000
.01 MFD
V210
6AK5
V211
6AK5
180
0.1 MFD
1800
.01 MFD
6800
2.2 K
1800
4700
.01 MFD
0.1 MFD
150
C 39
V213
6AG7
150
50
47 K
.01 MFD
100
.01 MFD
ALL CONDENSER VALUES ARE IN MICRO-MICROFARADS UNLESS OTHERWISE STATED.
ALL FEEDTHROUGH CONDENSERS ARE; 1500

for MTI

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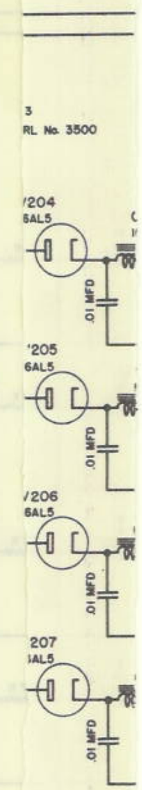
3
RL No. 3500



pensator

[redacted]

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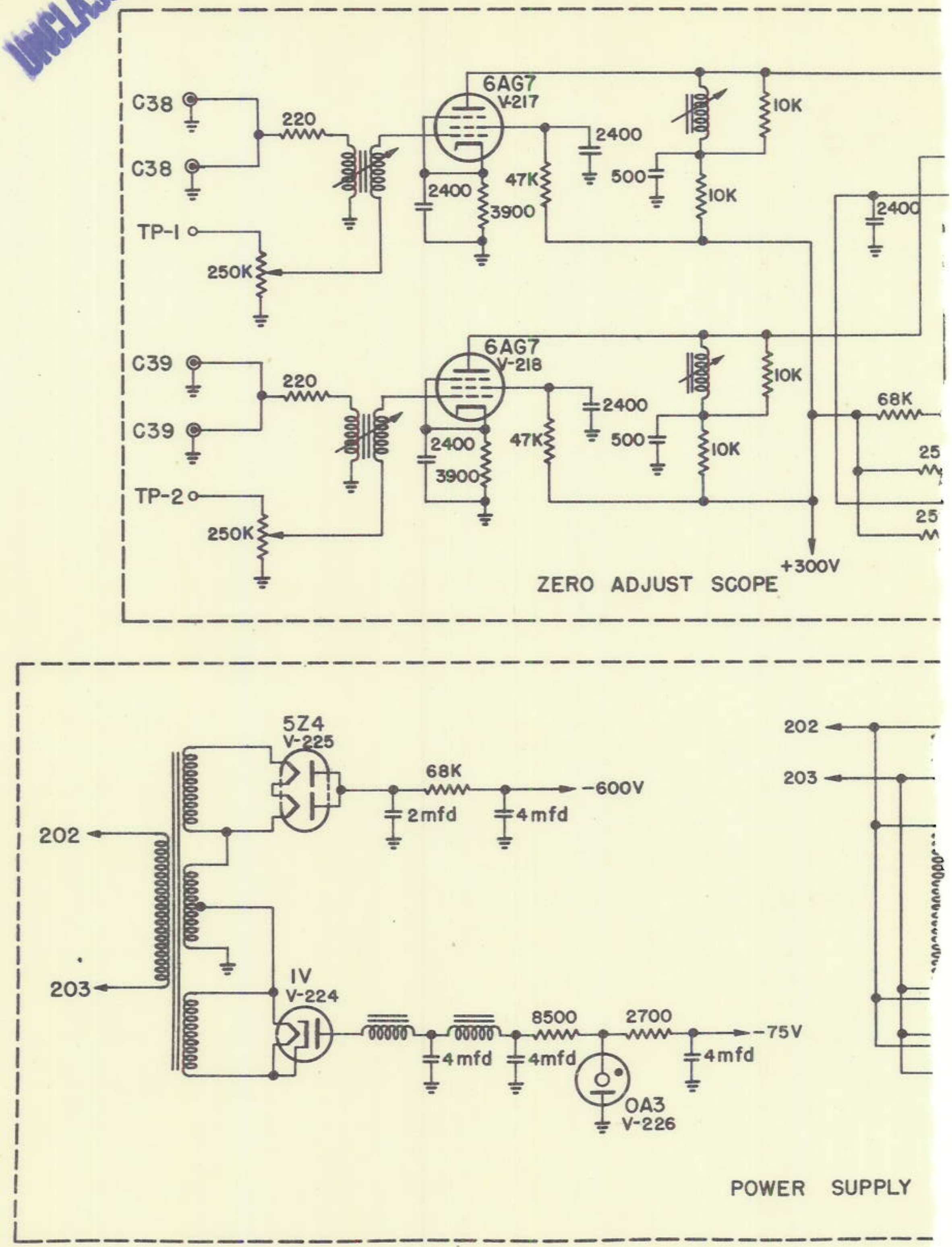

Diagrar

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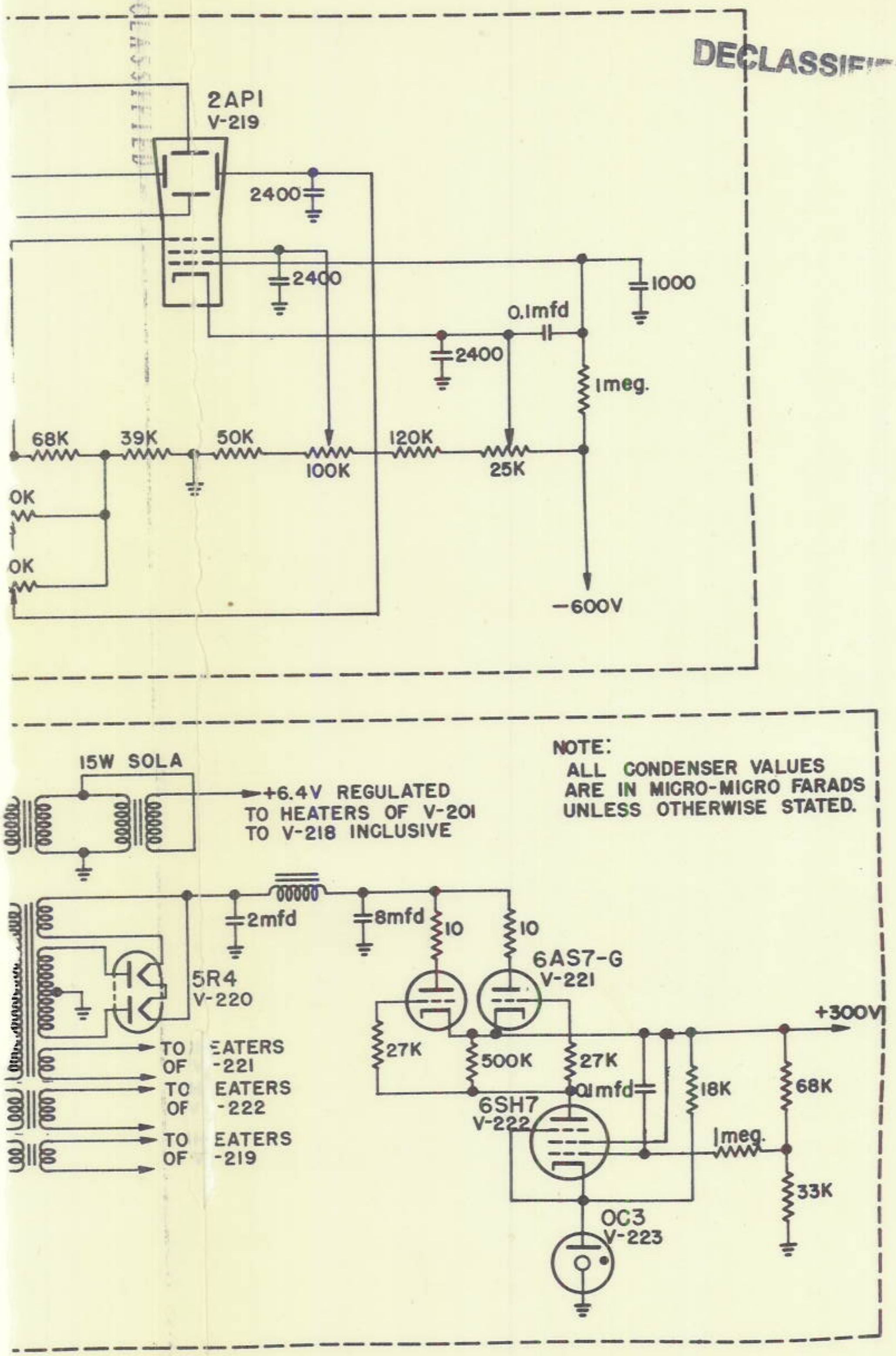
2API
V-219
2400
2400
1000
0.1mfd
2400
1meg.
68K
39K
50K
100K
120K
25K
OK
OK
−600V
15W SOLA
+6.4V REGULATED
TO HEATERS OF V-201
TO V-218 INCLUSIVE
NOTE:
ALL CONDENSER VALUES
ARE IN MICRO-MICRO FARADS
UNLESS OTHERWISE STATED.
2mfd
8mfd
10
10
6AS7-G
V-221
5R4
V-220
+300V
27K
500K
27K
.01mfd
18K
68K
6SH7
V-222
1meg.
33K
OC3
V-223
TO HEATERS OF V-221
TO HEATERS OF V-222
TO HEATERS OF V-219

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