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A NEW TECHNIQUE FOR DOPPLER FREQUENCY ANALYSIS OF RADAR SIGNALS--ETC(U)
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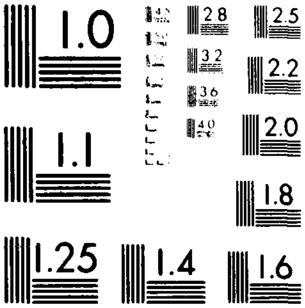
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A NEW TECHNIQUE FOR DOPPLER FREQUENCY ANALYSIS OF RADAR SIGNALS

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1. BACKGROUND

A longstanding performance goal for Army ground surveillance radars is the automatic classification of moving ground targets on the battlefield. Limited classification has been achieved by splitting the radar doppler spectrum into lower and higher frequency bands, thus distinguishing between targets having different radial velocities. While this is an important feature, since only certain targets (vehicles) are capable of obtaining high radial speeds, it does not provide a distinction between a moving man and vehicles having low radial speed components.

That there are distinct differences in the doppler signatures between man and vehicle is easily established by listening to typical doppler return signals. One can clearly distinguish the step modulation of a walking man from the relatively constant or slowly changing tone of a vehicle. As to be expected, a spectrogram of a walking man (~~Figure 1~~) shows this repetitive behavior. Most obvious is a sinewave like frequency modulation at the step frequency of the main body return power appearing as a black band near 100 Hertz.

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This oscillatory temporal characteristic in the doppler shifted frequency is practically never seen in vehicular return and is the discriminant chosen for automatic classification.

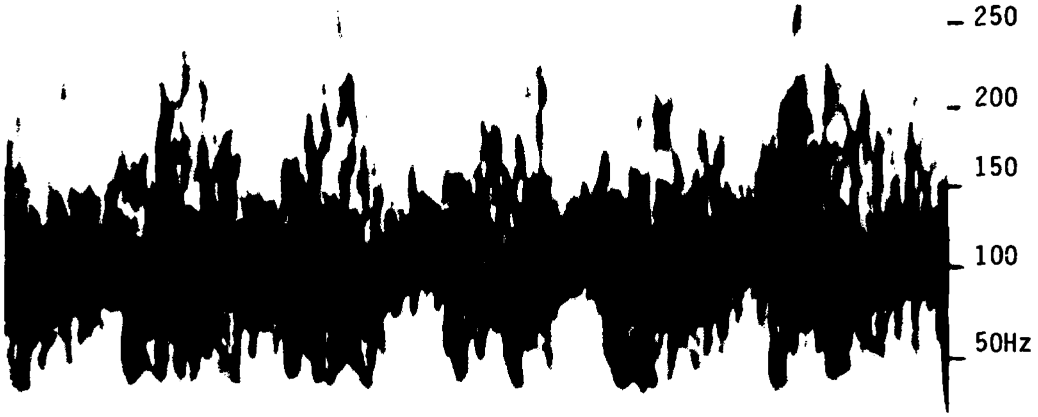

Figure 1: Doppler Spectrum of Walking Man

This paper describes efforts at the Combat Surveillance and Target Acquisition Laboratory at Fort Monmouth, NJ to develop an automatic classifier for moving personnel using a novel frequency locked loop to detect the modulation present in radar echos. After developing the theory, experiments are described and recommendations for further work are given.

2. THEORY

A coherent radar transceiver is used to obtain the doppler signal from a moving target. This signal is fed in a frequency locked loop using a frequency modulation discriminator to transform the momentary doppler frequency in a voltage. After the frequency loop locks on the target, the voltage proportional to the doppler frequency is analyzed for frequency modulation inafast fourier transform.

Its detector supplies signals to the display indicating the echo area, the radial speed and the step frequency (if any) of the target. Emphasis is placed on evaluation of different frequency locked loop variations of a novel discriminator.

For an uncluttered presentation, only the essential building blocks of the classifier are discussed. Also only the parameters relevant to the classification techniques described are included. When not essential, attenuation, phase and time delays are omitted or set to zero, oscillator signals have unit magnitude, multipliers have a multiplication constant of two and rectifiers give the magnitude of the input sinewave. Angular frequencies are used throughout. The main parts of the radar system are Transceiver, Frequency Modulation Transformer, Detector and Display.

Figure 2. Radar System for Automatic Identification

2a. RADAR TRANSCEIVERS: The doppler signal out of a radar is described by a magnitude m_d which is proportional to the target backscatter strength and the doppler frequency shift a_d. The output depends on the radar design and can be represented as $m_d\cos(a_o+a_d)t$, a sideband of an offset frequency a_o where a_o represents either the radio frequency, the intermediate frequency, or a natural number multiple of the pulse repetition frequency. In the homodyne transceiver case, both the inphase component $m_d\cos(a_o+a_d)t$ and the quadrature component $m_d\sin(a_o+a_d)t$ are needed to derive information on radial direction.

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2b. FREQUENCY MODULATION TRANSFORMER: The frequency modulation of the doppler return from a walking man is transformed into an amplitude modulation for further processing. The transformation is described in three steps: Frequency Sensitive Elements, Discriminator, and Frequency Locked Loop.

2bl. FREQUENCY SENSITIVE ELEMENT: Resonant circuits and R-C circuits are discussed.

2bIA. RESONANT CIRCUIT: Consider a tuned circuit of resonant frequency a and quality factor Q consisting of inductance L and a capacitance C in parallel ($a = 1/\sqrt{L.C}$), followed with a resistor R in series (normalized frequency $n = Q(a_S/a-a/a_S)$ with $Q = RaC = R/aL$), fed from a constant voltage source. For this configuration, the capacitances of the connecting lead and the load can be compensated by a corresponding reduction of capacitance C (figure 2bI). If the magnitude of the source signal is m_S and its frequency is a_S, the input voltage is $m_S \cos a_S t$. The output i across the tuned circuit is $o_i=(m_S/\sqrt{1+n^2})\cos(a_S t-\tan^{-1}n)$ and the output q across the resistor is $o_q= (m_S/\sqrt{1+1/n^2})\cos(a_S t+\cot^{-1}n)$. Since both output connections for o_q are floating, it is sometimes desirable to use the circuit of figure 2bIA where one output connection is grounded.

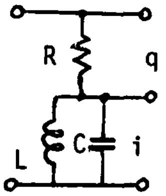

Fig. 2bI. Frequency Splitter

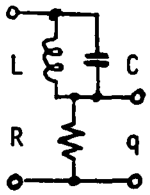

Fig. 2bIA. Frequency Stop

2bIB. R-C CIRCUIT: Since inductors are usually the largest, lossiest and most expensive tuned circuit elements, inductorless designs are included. The above formulas are then simplified by letting $L \rightarrow \infty$, resulting in resonant frequency $a = 0$, quality $Q = 0$ and the normalized frequency $n = RCa_S$.

2bII: DISCRIMINATOR: A conventional and a novel discriminator are treated.

2bIIA. CONVENTIONAL DISCRIMINATOR: After bandpass filtering the source signal with frequency a_s is fed with magnitudes m_- and m_+ to the filters Frequency Pass - and + (figure 2bIIA) whose resonant frequencies are a_- and a_+ (figure 2bI). Designating the inductances as L_- and L_+, the capacities as C_- and C_+, the resistances as R_- and R_+, the qualities of the tuned circuits as Q_- and Q_+, the normalized frequencies as n_+ and n_{-1}, the output signals as o_- and o_+, the outputs feed the twoway linear rectifiers + and -. The rectifier outputs o_+ and o_- feed the Subtractor, whose output $|o_+|-|o_-|$ is smoothed in the Lowpass filter, making its output $\overline{|o_+|-|o_-|} = m_+/\sqrt{1+n_+^2} - m_-/\sqrt{1+n_-^2}$. The amplitude versus frequency slope is s_+-s_- with $s = d(m/\sqrt{1+n^2})/d(a_s/\ a_m) = mnn'/\ (1+n^2)^3$ and $n'=dn/d(a_S/a_m)$, where $a_m = \sqrt{a_-a_+}$, the geometrical mean of the resonant frequencies.

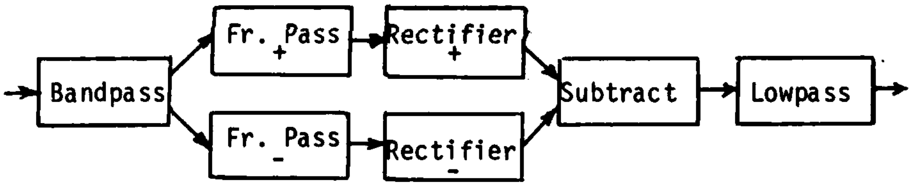

Figure 2bIIA: Conventional Discriminator

For the special case of equal signal magnitudes $m_- = m_+ = m_S$ and equal quality $Q_- = Q_+ = Q$, the output is $m_S.(1/\sqrt{1+n_+^2} - 1/\sqrt{1+n_-^2})$. For large normalized frequencies this approximates $2m_s(a_m-1)/(Qa_s/a_m)$. The slope at the a_m becomes then $2m_sQ^2(a_m^2-1/a_m^2)/\{\sqrt{1+[Q(a_m-1/a_m)]^2}\}^3$ Figure 2bII shows the lowpass output and its contributions from Frequency Pass - and + for unit source signal magnitude $m_- = m_+ = m = 1$,

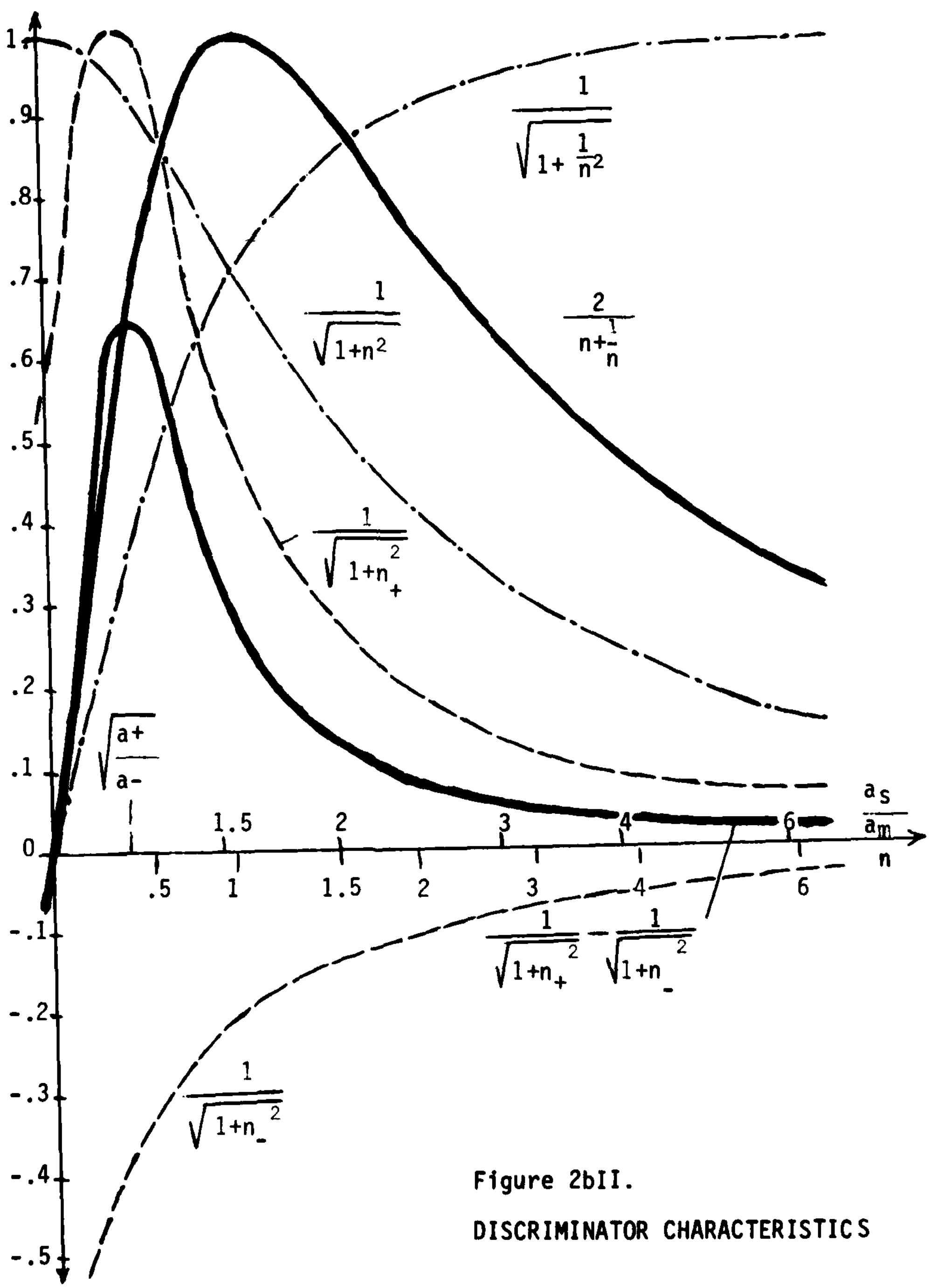

Figure 2bII.

DISCRIMINATOR CHARACTERISTICS

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Quality $Q_- = Q_+ = 12$ and resonance frequency ratio $a_+/a_- = 1.44$. The slope for $a_S = a_m$ is 4.2354 at the origin.

2bIIB. <u>NOVEL DISCRIMINATOR</u>: The preferred characteristic of a discriminator has odd symmetry response with respect to a center frequency. The susceptance of a lossless tuned circuit $j(aC-1/aL)$ has this property, but approaches infinity for frequencies nearing zero or infinity. A response which decreases at the extreme frequencies as with the conventional discriminator, can be achieved by correlation using resonant or R-C circuits.

2bIIB1. <u>RESONANT CIRCUIT CASE</u>: A source signal $m_S \cos a_S t$ is fed into the Pass filter for rejection of undesired frequencies. The Frequency Splitter (figure 2BIIB1) outputs i and q are fed into Phaseshifters i and q with phaseshifts p_i and $p_q = p_i + 90^0$ to supply cosine signals with magnitudes $m_S/\sqrt{1+n^2}$ and $m_S/\sqrt{1+1/n^2}$, and phase $|a_S| t + p_i - \tan^{-1} n$ to the Multiplier with constant M, whose output $[Mm_S^2/2(n+1/n)][1-\cos 2(|a_S| t + p_i - \tan^{-1} n)]$ is fed to the Lowpass, which removes the alternating part, leaving $Mm_S^2/2(n+1/n)$. For small and large normalized frequencies, this can be approximated by $Mm_S^2 n/2$ and $Mm_S^2/2n$. At the origin of Figure 2bII $n = o$ and the slope, $Mm_S^2(n-1/n)/2n(n+1/n)^2$, becomes $Mm_S^2/2$ giving an output of $Mm_S^2 n/2$. The slope vanishes for $n = \pm 1$, where the outputs become the extremes $\pm Mm_S^2/4$. For large n the output is about $\pm Mm_S^2/2n$.

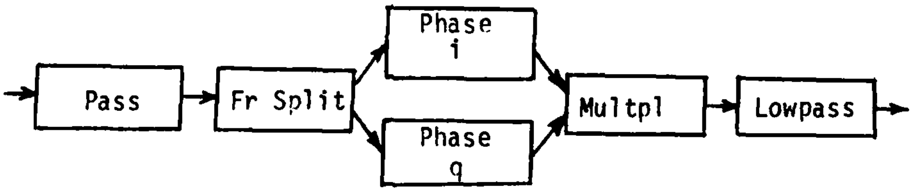

Figure 2bIIBI: NOVEL DISCRIMINATOR

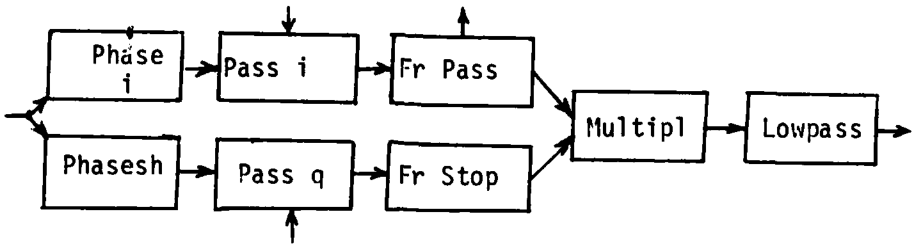

Figure 2bIIB2: NOVEL DISCRIMINATOR

For comparison of both types of discriminators it is assumed that their noise outputs are equal as well as the dynamic range of their nonlinear elements, the rectifiers and multipler. Setting the maximum input voltage to unity for both should make the output of the nonlinear element equal at the extremes. Since this was set to unity for the conventional discriminator, the multipler contant becomes M = 4. In addition, the slope of both discriminators shall be equal at the origin. Since the slope for the conventional discriminator was given in units of source over resonant frequency, the slope for the Novel Discriminator with respect to the normalized frequency has to be multiplied with the derivative of the normalized frequency to source over resonant frequency: $(Mm_S^2/2)(d\ n/d\ a_S/a) = (4.1^2/2)[d\ Q.(a_S/a-a/a_S)]$ $/(d\ a_S/a) = 2Q[1+(a/a_S)^2] = 4Q$, since at the origins source and resonant frequency coincide. Setting both slopes equal gives 4.2354 = 4Q or Q = 1.0594 (figure 2bII). For this case, the outputs for large normalized frequencies are about 16 times larger for the Novel Discriminator.

An equivalent circuit to figure 2bIIB1 is shown in figure 2bIIB2. The phaseshifters have been shifted to the input, requiring the Pass function to be performed by Pass i and Pass q and the Frequency Splitter function by Frequency Pass and Frequency Stop.

If the source signal consist of two sinusodial signals with magnitudes m_1 and m_2 and with frequencies a_1 and a_2, the series of Frequency Splitter and Phaseshifter i and q gives outputs (figure 2bIIB1) of: $(m_1/\sqrt{1+n_1^2})\cos(|a_1|t+p_i-\tan^{-1}n_1)+(m_2/\sqrt{1+n_2^2}).\cos(|a_2|t+p_2-\tan^{-1}n_2)$ and $(m_1/\sqrt{1+1/n_1^2})\cos(|a_1|\ t+p_i-\tan^{-1}n_2)+(m_2/\sqrt{1+1/n_2^2}$ $\cos(|a_2|t+p_2-\tan^{-1}n_2)$. Both are fed into the Multipler, that forms 4 products equivalent to 8 frequency components. The Lowpass rejects all alternating parts, leaving $M[m_1^2/(n_1+1/n_1)+m_2^2/(n_2+1/n_2)]$. For the case of equal magnitudes $m_1 = m_2 = m$ and about equal frequencies, the output can be approximated by $Mm^2(n_1+1/n_2)/2$.

2bIIB2. <u>R-C CIRCUIT CASE</u>: The inductances are left out of the tuned circuit ($L \rightarrow \infty$). The Pass or Pass i and q are now lowpasses. If the signal is applied as shown in figures 2bIIB2, only positive output values corresponding to positive n in figure 2bII are achievable, since one input frequency is all times assumed to be positive. But if two out-of-phase source frequencies are available as from a quadrature homodyne receiver and they are applied to the inputs of the Pass i and q of figure 2bIIB2, the full output range can be covered (including negative values). The lowpass output is now $(|a_S|/a_S)Mm_S^2(RCa_S+1/RCa_S)$.

2bIIC. <u>USE OF DISCRIMINATOR</u>: Despite its lower dynamic range, the conventional discriminator with its many variable parameters has potential for a larger linear range near the origin than the Novel Discriminator. But using a discriminator directly as in frequency modulation broadcast receivers is not desirable, since the radar echo from walking man changes in amplitude and is mixed with noise and sometimes other doppler signals from different speed targets and windblown clutter. Clipping before discriminating will erase amplitude modulation, but is a far cry from matched filtering, since it gives equal emphasis to small and large returns, thereby increasing the nonsignal contributions.

2c. FREQUENCY LOCKED LOOP: The disadvantages of clipping can not only be avoided by using a frequency locked loop but an additional increase in signal-to-noise-ratio is possible by having an increased gain of the discriminator circuit near its axis of asymetry, where the correction signal for the control voltage most of the time will appear. Outside this narrow band the gain should be lower but stay above a certain minimum level for timely aquisition of a newly appearing target echoe at any frequency of the selected doppler band.

The output of the conventional discriminator increases proportional to the input magnitude, while the novel discriminator follows a square law response. If the Lowpass has a long storage time, the outputs for changing inputs are averaged. But a square law response gives heavier emphasis to times with higher input signals and therefore higher signal-to-noise ratio. For these reasons, only the Novel Discriminator will be considered further on. Signal bands being centered and onesided to an offset frequency a_0 are being treated.

2cI. SIGNAL BAND CENTERED AT OFFSET FREQUENCY: The direct doppler return is used or its conversion to an intermediate frequency by either an intermediate receiver or by a pulse quadrature receiver. Frequency locked loops using discriminator with resonant and R-C circuits are treated.

2cIA. USING DISCRIMINATORS WITH RESONANT CIRCUITS: After filtering in Pass i, the signal supplied by the radar receiver $m_d\cos(a_0+a_d)t$ is multiplied with an oscillator signal, at frequency a_c having a unit amplitude, $\cos a_ct$, in Multipler i (figure 2c), providing a signal $m_d[\cos(a_0+a_d-a_c)t+\cos(a_0+a_d+a_c)t]$ to the discriminator, whose Pass (figure 2bIIB1) rejects the sum frequency. The difference frequency becomes the source frequency $a_S = a_0+a_d-a_c$ with

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a magnitude of $m_S = m_d$. For zero doppler shift, both source and resonant angular frequency should be equal $a_S = a_1$ while the normalized angular frequency and the output signal vanish: $n = Mm_d^2/2(n+1/n) = 0$, making the oscillator frequency to a_0-a. Approximating the oscillator behavior by a linear characteristic with a slope F gives therefore $a_c = a_0-a+FMm_d^2/2(n+1/n)$. This equation does not yield a simple solution. But after frequency lockis achieved, only the discriminator characteristic part near the origin is used, where the slope is MQm_d^2, so that $a_c = a_0-a+FMQm_d^2(a_S-a)/a$. This gives the discriminator output as $a_d/(F+a/MQ.m_d^2)$, which approaches for large signal magnitudes a_d/F.

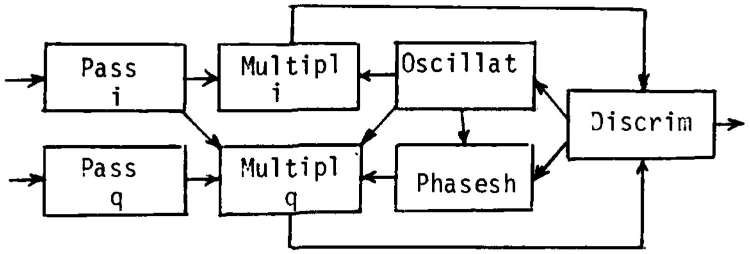

Figure 2c: Frequency Locked Loop

2cIB. USING R-C CIRCUITS: The signal $m_d\cos(a_0+a_d)t$ is let through Pass i for Multipliers i and q, whose other inputs are $\cos a_ct$ from the Oscillator and $\sin a_ct$ from the Phaseshifter, whose input is also supplied from the Oscillator (figure 2c). The Multiplier i and q outputs $m_d.[-\cos(a_0+a_d-a_c)t + \cos(a_0+a_d+a_c)t]$ and $m_d[-\sin(a_0+a_d-a_c)t+\sin(a_o+a_d+a_c)t]$ are fed to discriminator Pass i and q (figure 2bIIB2), which reject the sum frequencies signals. The difference frequency acts as source frequency $a_S = a_0+a_d-a_c$ as before. But since the slope at the origin is now $Mm_s^2RC/2$ and the resonant frequency vanishes a=0, the oscillator angular frequency is approximated as $a_c = a_0+FMm_d^2RCa_S/2$, giving the output of the Discriminator as $a_d/(F+2/RCMm_d^2)$, which again approaches a_d/F for large magnitudes.

2cII. ONESIDED SIGNAL BANDS : To preserve information of radial direction, two quadrature inputs at the same frequency band are needed. Only the discriminator using R-C circuits is suited. Signal with and without offset frequencies are treated.

2cIIA. NON-BASEBAND SIGNALS: From a quadrature pulse receiver both lower or both upper sidebands of a integral multiple greater than zero of the pulse repetition frequency are suitable. The signals $m_d \cos(a_0+a_d)t$ and $m_d \sin(a_0+a_d)t$ are fed through Pass i and q (figure 2c) to Multiplers i and q, whose other inputs cos $a_c t$ are supplied by the Oscillator. The Multiplier i and q outputs $m_d[\cos(a_0+a_d-a_c)t + \cos(a_0+a_d+a_c)t]$ and $m_d[-\sin(a_0+a_d-a_c)t+\sin(a_0+a_d+a_c)t]$ are fed to discriminator Pass i and q (figure 2bIIB2) which rejects the signals with sum frequencies. The leftover signal at the source frequency of the discriminator $(a_0+a_d-a_c = a_S)$ is centered around an frequency $a_0+a_M-a_c$ (where the middle frequency of the doppler band is symbolized as a_M), which should be zero for optimum discriminator performance, This makes the oscillator frequency equal to a_o+a_m for zero input and in general $a_c = a_0+a_M+FMRCm_d^2 a_S/2$. This yields a discriminator output of $(a_d-a_M)/(F+2/MRCm_d^2)$, which approaches $(a_d-a_M)/F$ for large magnitudes.

2cIIB. BASEBAND SIGNALS: This includes doppler signals from quadrature homodyne receivers and the baseband signals of quadrature pulse receivers. The signals $m_d \cos a_d t$ and $m_d \sin a_d t$ are fed through Pass i and q (figure 2c) to Multiplers i and q, whose other inputs are cos $a_c t$ from the oscillator and $\pm\cos a_c t$ from the phase-shifter. The Multiplier i and q outputs $m_d[\cos(a_d-a_c)t+\cos(a_d+a_c)t]$ and $m_d[-\sin)(a_d \pm s a_c)t + \sin(a_d \pm a_c)t]$ are fed to discriminator Pass i and q (figure 2bIIB2), which attenuates the sum frequency signals only if their frequency exceed the cut off frequency of the Passes i and q. In this case, the further processing is the same as in 2cIIA, but with an offset frequency $a_0 = 0$.

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But if the sum frequency does not exceed the cut off frequency of the Passes i and q, the difference as well as the sum frequencies are sent to the Frequency Pass and Stop. After track is acquired, doppler and oscillator frequencies are about the same and the output of the lowpass can then be approximated by $Mm_d^2(n_1+1/n_2)/2$ with $n_1 = RC\,(a_d \pm a_c)$ and $n_2 = RC(a_d \mp a_c)$. Without input, the oscillator frequency is equal to the middle frequency, therefore $a_c=a_M+FMm_d^2(n_1+1/n_2)/2$. By approximating the sum frequency by two times the doppler $a_d \pm a_c=2a_d$, the discriminator output is $(a_d-a_M+1/2a_d)/(F+2/MRCm_d^2)$. For large magnitudes, the discriminator output is $(a_d-a_M+1/2a_d)/F$. Whenever the output of the discriminator has a negative value sufficient to drive the oscillator below the lowest expected absolute doppler frequency, it forces the Phaseshifter to change the polarity of its output, thus both incoming and outgoing targets can be tracked.

2d. <u>DETECTOR AND DISPLAY</u>: The signal at the Frequency Splitter i or Frequency Pass output is rectified and monitored by a threshold. If a preset level is exceeded an analog-to-digital converter digitizes the echo magnitude for display (figure 2d). Also, the discriminator lowpass signal is fed in a Fast Fourier Transformer, and detected. Outputs exceeding a minimum level are converted and displayed, including the d.c. output giving the average doppler frequency. Since the modulation frequency even for running man is only a few Hertz, the Fast Fourier Transformer and A/D Converter can be time shared by many channels.

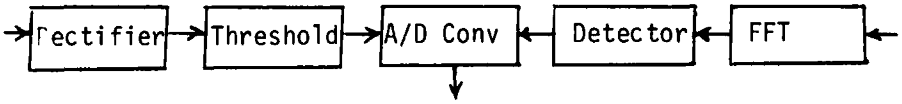

Figure 2d: Detector for Frequency Locked Loop

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EXPERIMENTS

A frequency locked loop using the Novel Discriminator with R-C circuit was built. An endless loop with the recording of a radially walking man using the base channel of a simple pulse radar supplied the input voltage to both phaseshifters i and q (figure 2bIIB2). The discriminator output was monitored with a digital voltmeter and a recording real time spectrum analyzer. The signal fora walking man presented clearly the doppler speed and the step frequency. It was also observed, that the power of the doppler signal has a small spectral component at the step frequency.

CONCLUSION AND RECOMMENDATIONS

While the limited experiments proved the feasibility of automatic classification of a walking man, a wide range of experiments should be conducted to determine the influence of speed and angle towards the radar of different single and multiple targets, noise, moving clutter, antenna modulation and observation time. Also the replacement of multipliers by modulators should be investigated to minimize power consumption.

The Novel Discriminator should have a wide range of applications in systems benefiting from frequency locked loops.

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