Correspondence

Delay-Lock Repeater Tracking System Utilizing Superregenerative Interrogator

Abstract

A unique delay-lock tracking system is described. The system includes an interrogator and a repeater operating on the same radio frequency, with a pulse repetition rate which is related to the distance. Single radio frequency operation allows utilization of a superregenerative radio frequency stage, which serves as both the receiver and the transmitter of the interrogator unit.

I. Introduction

The system described here belongs to the family of delay-lock tracking systems [1]. It is an extension of the development of a delay-lock radio altimeter described previously [2]. The system utilizes a slightly modified altimeter as the interrogator. However, the passive terrain return is replaced by an active repeater, the distance to which is sought. In addition to its increased return power over most passive targets, the active repeater has the ability to add any requested length of delay. Such a delay could be used to eliminate ambiguity problems and to improve the signal-to-clutter ratio.

The second characteristic of the system is the use of a superregenerative radio frequency stage. The superregenerative stage [3] is a pulsed fundamental oscillator, whose biasing and tuning are adjusted so that the time length of the oscillations' buildup from noise will consume a significant portion of the overall pulse length. In the presence of a received signal, whose frequency is in the vicinity of the oscillator's natural frequency and whose timing coincides with the oscillations' starting point, the oscillations' buildup will begin from a higher initial value, increasing the oscillator's radio frequency power per pulse.

The superregenerative effect should be found in any type of fundamental oscillator, including those based on microwave semiconductor devices such as Gunn diodes [4] and avalanche diodes [5]. The superregenerative stage used in our prototype system operates at 430 MHz and utilizes a transistorized stripline oscillator.

II. Principle of Operation

A timing diagram of an unambiguous system is given in Fig. 1. A search sequence at the interrogator is represented on the upper time axis. The interrogator receiver has a narrow receiving window followed, after a very short delay τ_s, by a transmitted pulse. The pulse is transmitted whether or not a pulse was received during the opening of the receiving window. After a period T, the receiving window opens again, followed by a transmitted pulse, and so forth, repeatedly. As long as locking is not achieved, the period T

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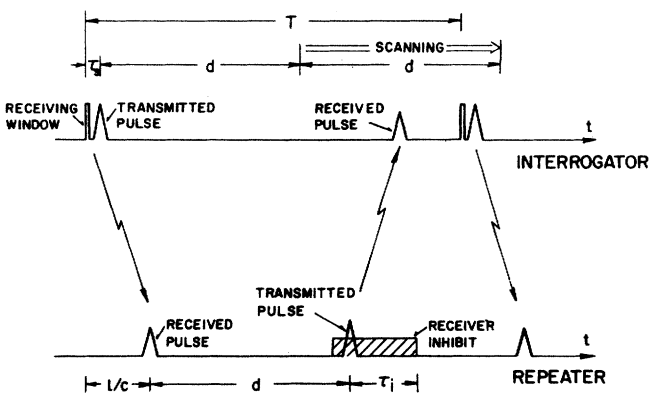


Fig. 1. Timing diagram of the system.

is varied slowly over the range

$$d + \tau_s < T < 2d + \tau_s.$$

The period d is chosen to be approximately equal to the length of time required by the pulse to traverse the maximum range $L_{\max}$ which the system is expected to measure, i.e.,

$$d \approx 2L_{\max}/c$$

where c is the velocity of propagation.

The receiver part of the repeater is open most of the time. Any received pulse triggers a transmitted pulse after a fixed and very stable delay. (The delay also equals d.) The pulse transmitted by the repeater arrives back at the interrogator after a total delay of $d + 2L/c$. As long as the interrogator period T (less τ_s) is not equal to this delay, the arriving pulse will not coincide with the receiving window; and the interrogator, which will not be able to detect it, will continue its scanning. The system locks when

$$T = d + \tau_s + 2L/c. \tag{1}$$

The interrogator's short delay τ_s is inherent in its superregenerative radio frequency stage. The repeater's longer delay d is introduced to eliminate ambiguity. Both should be fixed and known to a high degree of accuracy.

III. The Interrogator

A block diagram of the interrogator is given in Fig. 2. The receiving window and the transmitted pulse are both functions of the superregenerative radio frequency stage. The receiving sensitivity at the beginning of the oscillations' growth is the receiving window. When the oscillations reach saturation they become the transmitted pulse. A feedback loop in the bias circuit maintains a constant-width transmitted pulse, while the detected signal is extracted from the bias itself. The superregenerative stage has three additional advantages: its gain is logarithmic; its dynamic range is extremely wide; and its transmitting frequency is inherently equal to its receiving frequency.

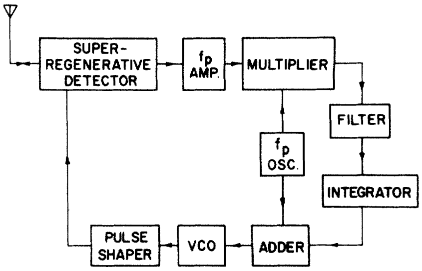
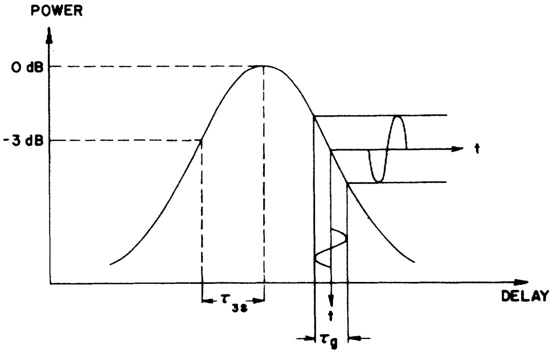


Fig. 2. Block diagram of the interrogator.

Fig. 3. Perturbation signal detected on the slope of a returning pulse.



Any pulse transmitted by the interrogator returns from the repeater after a delay determined by the distance between the two, plus the internal delay in the repeater. The interrogator's loop causes the receiving window to scan the relevant delay range. When the receiving window coincides with the arrival time of the peak of the returning pulse it locks and stops scanning. The interrogator's pulse repetition period T is varied by a voltage-controlled oscillator (VCO) fed by an integrator. Before the loop locks, a small pushing voltage at the integrator input causes its output to assume the form of a voltage ramp. Hence, the VCO period T increases continuously. (The receiving window slowly recedes from the previously transmitted pulse.) This scanning direction will improve the system's chance of locking on the direct wave rather than on multipath waves. The fixed scanning rate is modulated by a small sinusoidal (or other waveforms) perturbation at a perturbation frequency f_p. When the scanning receiving window approaches the returned pulse, the perturbation will be detected on the slope of that pulse (Fig. 3). The detected perturbation will either be in phase or out of phase with the injected perturbation, depending on whether the receiving window scans the leading edge or the trailing edge of the incoming pulse.

Multiplying the detected perturbation by the injected perturbation will yield a dc component, positive or negative, as an error signal to be fed to the integrator after appropriate filtering. When the receiving window coincides with the peak of the pulse, this synchronous detection yields zero average output; the integrator output remains constant; and the system locks. In other words, introducing the perturbation is equivalent to taking the derivative of the returned pulse. In a way, the perturbation is similar to the split-gate technique common to many tracking systems.

The lower limit on the loop bandwidth is determined by the scanning rate or the distance rate of change, whichever is greater. An upper limit is determined by the pulse repetition rate. The loop will obviously be adjusted to operate near its lower limit.

The interrogator's operation was described as a narrow gate sampler (the receiving window of the superregenerative stage), an averaging mechanism (the loop), and a split gate operating on the average detected pulse (the perturbation of the repetition rate).

Some idea on the random range error contribution by the superregenerative interrogator could be deduced from an available analysis by Barton and Ward [6]. This analysis gives the rms time delay error as a function of the input signal for a tracking system including a square split gate operating on a Gaussian return pulse which has passed through a wide bandwidth Gaussian filter. According to [6] the pulse peak power P_i required to get a requested normalized delay error σ_τ/τ_{3s} is given by

$$P_i = 2.15 \left(\frac{\sigma_\tau}{\tau_{3s}}\right)^{-2} \left(\frac{\tau_g}{\tau_{3s}}\right)^{-3} \frac{B_L N_0 F}{f_q \eta_f \tau_{3s}} \tag{2}$$

where

$$\eta_f = \frac{2B_h/B_s}{1 + (B_h/B_s)^2}$$

and

$$B_h > B_s$$

$$\tau_g < \tau_{3s}.$$

A list of symbols and typical values for an interrogator operating at 430 MHz are given in Table I.

TABLE I

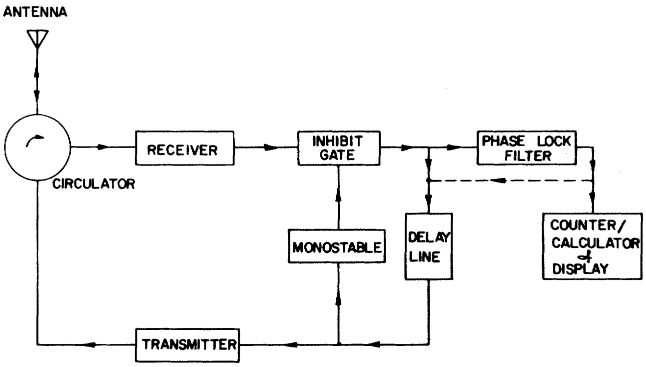
Symbol	Meaning	Typical Value
B_h	rms width of superregenerative stage transfer function	33.2 MHz
B_s	rms width of signal voltage spectrum	8.3 MHz
B_L	overall interrogator loop bandwidth	2 Hz
F	radio frequency stage noise figure	8
f_q	pulse repetition frequency	20 kHz
η_f	efficiency factor	
N_0	density of uniform noise	5×10^{-21}W/Hz
P_i	peak power of returned pulse	2.35×10^{-12} watts
τ_g	split-gate width	0.05 μs
τ_{3s}	half-power width of signal	0.2 μs
σ_τ	rms time-delay error	0.01 μs (1.5 meters)

It should be emphasized again that (2) does not apply directly since the perturbation waveform is not square; the pulse shape is not Gaussian; and the superregenerative stage does not have a Gaussian response, and its detection law is logarithmic rather than linear.

IV. The Repeater

The repeater is conventionally constructed from a receiver and a separate transmitter (Fig. 4). The receiver is designed to detect the peak of each interrogator's pulse. Each detected pulse triggers, after a delay, a transmitted pulse. To prevent periodic false alarm, with a period equal to the delay, an inhibit gate blocks the receiver output when a pulse is being transmitted. The period of the remaining detected pulses is a measure of the distance. A counter/calculator and display unit is used to measure this period, to calculate the corresponding distance, and to display the result.

Fig. 4. Block diagram of the repeater.



The receiver part of the repeater detects the interrogator pulses, noise, and its own pulses after they are backscattered from nearby objects. Noise pulses will cause false alarms, generating unsynchronized transmitter pulses from the repeater. The basic disadvantage is an increase in the average power consumed by the repeater. The interrogator will see those false returns as a small increase in the noise level. An additional inconvenience caused by these noise false alarms is that the pulses' period at the receiver output (after the inhibit gate) cannot be counted directly, but only after phase-lock filtering.

The backscattered pulses constitute a more serious problem because the false self-triggering that they cause is not random but periodic. This can confuse the phase-lock filter (PLF) and cause erroneous display of the distance. Backscattered power is attenuated following a law of fourth power of distance. Hence, strong backscattered returns can come only from nearby objects. To overcome the backscattering problem, the inhibit period τ_i is extended by a monostable. An increase in the inhibit period imposes an increase in the minimum measurable range, i.e., the system cannot measure distances below $L_{\min}$ given by

$$L_{\min} = (\tau_i - \tau_s)c/2, \quad \tau_i \geq \tau_s. \tag{3}$$

The backscattering problem does not exist at the interrogator's side. There the receiving window opens after a delay of d at least. The system can easily be adjusted so that no backscattered return from a distance farther than the maximum range for a repeater return could possibly be strong enough to cause false locking.

V. Inclusion of the Repeater PLF Inside the Loop

One possible variation in the repeater design is to connect the delay line after the PLF rather than in front of it and to use the PLF as a tracking filter. This change eliminates the falsely transmitted pulses triggered by noise and backscattering. However, in order for all the repeater pulses to be returned to the interrogator after a fixed delay, the PLF has to be of such a high bandwidth that the perturbation signal will pass through it without significant phase and amplitude errors. The PLF natural frequency should be approximately ten times the perturbation frequency. For comparison, the PLF bandwidth when outside the loop can be smaller than the perturbation, and an average reading is sufficient. The PLF bandwidth when outside the loop is determined only by the requirement on acquisition time.

The PLF when included in the repeater loop will also serve as the pulse peak position detector. To achieve that, the reference signal multiplying the incoming signal should have the shape of a narrow split gate rather than of a square wave (Fig. 5). The gate width should be only slightly wider than the incoming pulsewidth, and the period will be voltage controlled, as in a regular PLF. By using such a narrow split gate, backscattered returns will be multiplied by the zero level of the reference signal and will not be able to cause an average shift in the gate position. Furthermore, noise-generated jitter in the gate position will be reduced.

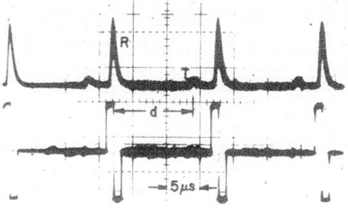


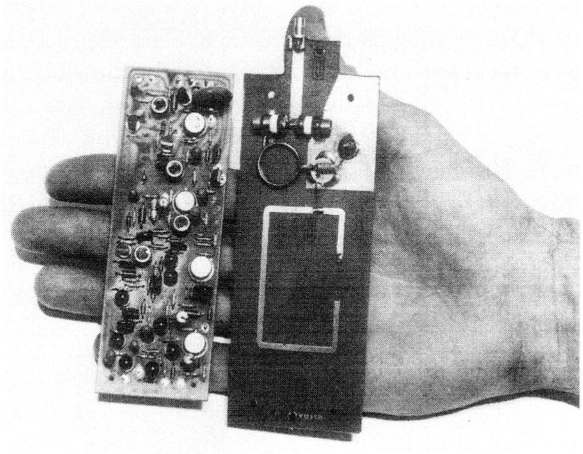
Fig. 5. Received (R) and partially blanked transmitted (T) pulses of a repeater which includes a split-gate PLF in its loop.

The main disadvantage of including the PLF in the loop is the complication of lock acquisition, because we now have two phase-lock loops locked on each other. The narrow pulses and the narrow split-gate reference signal make acquisition even harder. An important advantage of including the PLF in the loop is the elimination of the need for detecting the pulses' peak position on a single-pulse basis. In the presence of noise, such accurate peak position detection is not easily implemented.

VI. Experimental Results

Field tests were conducted using a prototype system. Fig. 6 shows the interrogator's electronics. Repeaters of both types (PLF inside and outside the loop) were used. Some parameters of the system are the following:

Fig. 6. Interrogator.



radio frequency	430 MHz
peak radio frequency power	
interrogator	1 watt
repeater	1 watt
pulse 3-dB width	0.2 μs
pulse repetition frequency	20-80 kHz
perturbation frequency	200 Hz
antennas	5 elements Yagi
scanning rate	0.5 μs/s
interrogator	
average input power	0.6 watt
weight	7 ounce (not including power source)
overall loop bandwidth	2 Hz

The maximum distance through which locking was maintained was 7 km over a suburban area without line of sight. The following test was conducted to demonstrate resolutions. A person carrying the interrogator was traveling in a circle 20 meters in diameter, at a distance of approximately 1.5 km from the repeater. The measured distance was printed at the repeater end every 2.5 seconds, and Fig. 7 shows the resulting graph. The repeater used in this experiment had its PLF outside the loop. Because the required pulse-peak position detector was not available, a threshold-crossing detector was used. This simpler detector is sensitive to pulse intensity. Slight changes in pulse intensity from one end of the circle to the other caused the peak-to-peak distance of the sinusoid in Fig. 7 to be slightly larger than the circle diameter. The linear section in Fig. 7 corresponds to a period during which the interrogator was placed at the center of the circle. The measured rms value of the random error calculated from this section is 35 cm.

VII. Conclusions

In this work we have demonstrated the distance-measuring capability of a delay-lock system that utilizes a repeater and a superregenerative interrogator, both of which operate on the same radio frequency.

The distance-measuring range of the system could be increased by increasing power and/or antenna gain on the repeater side. Radio frequency could also be increased because most of the microwave semiconductor oscillators yield to superregeneration.

The character of the repeater (the version with the PLF outside the loop) allows it to respond to several inter-

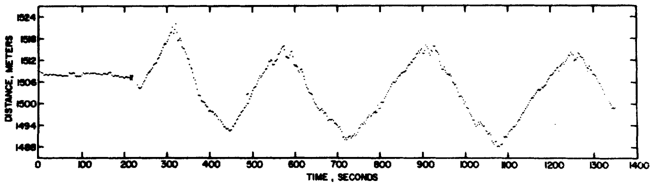


Fig. 7. Distance measured to the interrogator when an individual carries it around a circle of 20-meters diameter at a distance of 1.5 km.

rogators simultaneously. The distance to the repeater will be extracted at each interrogator. The repeater will be able to distinguish between the interrogators if a different perturbation frequency is assigned to each one.

Information could be modulated on the interrogator-to-repeater link by varying the perturbation frequency. Simultaneously, information at lower rates could be modulated on the repeater-to-interrogator link by varying the length of the repeater's internal delay.

A receiver located near either the repeater or the interrogator, and receiving only one, will be able to detect the data originated at both. Hence, a case of a "same frequency communication repeater" results. The same is true for a receiver located within receiving range of both ends.

Finally, after building the whole concept around the superregenerative stage, we can retain the concept but eliminate the superregenerator. A receiving window followed by a transmitted pulse could be achieved by more conventional methods, such as a gated receiver followed by a separate transmitter. If the application calls for it, and allows for the loss of simplicity, a conventionally built interrogator could achieve higher power and better sensitivity.

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On the Optimum Squint Angles of Amplitude Monopulse Radar and Beacon Tracking Systems

Abstract

The different quantitative criteria (and numerical results) for analytically determining the optimum squint angle of an amplitude monopulse system in the track mode are compared and reconciled, and the results are generalized to include mutual coupling.

Most prior works agree on the choice of boresight sensitivity as the significant "quality factor" to be optimized in amplitude monopulse tracking radars. However, different authors [1], [2] have quantified this notion in different ways and have been thus led analytically to different choices of optimum squint angles φ_s. Thus in [1] and [2] the optimum φ_s leads to beam crossover at about 3 dB and about 1 dB, respectively. This correspondence examines the exact process of quantification used and breaks this procedure down into two stages. The first stage is somewhat arbitrary and motivated by physical intuition. However, the second stage appears to be linked to whether a radar or beacon system is under consideration. By properly applying this observation it is demonstrated analytically and numerically how the two different quantitative criteria in [1] and [2] are in fact identical when viewed from the proper perspective and yield the identical results for the same type of tracker. These results are then generalized to take into account the mutual coupling between the monopulse antenna beams.

Rhodes has discussed in [1, sec. 6.3] why "no squint angle exists that maximizes sensitivity within the main beam" for his definition of boresight sensitivity. However, he explores several related quantities and selects the maximum slope-sum product as probably the most useful quantity to use to choose an optimum squint angle. This is

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