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Phase-Switched FM-CW Radio Altimeter

By

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Summary: The radio altimeter with frequency modulated signal and frequency counting type of processing is investigated from the view point of airborne sensor at landing. The phase switching of transmitting signal is newly proposed to reduce the step error of processing. The phase switching technique is applied to the altimeter with frequencies, 4000 MHz of carrier and 100 MHz of band width. Some results of experiment are described with theoretical analysis.

1. INTRODUCTION

The air-borne radio altimeter is used mainly at low altitude, especially in landing phase, because it can provide an aircraft with more precise information of height than other types of altimeter. The radio altimeter would be classified into two types of radar, the pulse radar and the continuous wave (CW) radar. There are mentioned, in this paper, studies about the frequency modulated (FM-CW) radar combined with frequency counting method of signal processing i.e. FM-counting type of altimeter, through analysis and experiments. It is also given a new proposal about the modulation, which can improve the accuracy of height measurement.

Studies are made from the point of view how to improve the radio altimeter that would be the height sensor of autolanding; the conditions are listed below that should be satisfied by the altimeter:

(1) The altimeter should operate under the height of 100 m. (Especially it must be highly reliable under the height of 30 m.)

(2) The error of measurement should be within ±0.2 m. (The measurement should be made about the absolute height to the runway.)

(3) The time delay of measurement (the allowable time to measurement) should not exceed 0.05 sec. (Through the height information, the instantaneous vertical velocity must be obtained, which will be under 4 m/sec from flare-out to touch down.)

2. BASIC CHARACTERISTICS OF FM-COUNTING TYPE RADIO ALTIMETER

2-1 Principle

The principle and basic composition of FM-CW radar are shown in Fig. 1 and Fig. 2. The transmitted signal is frequency-modulated by a triangular wave;

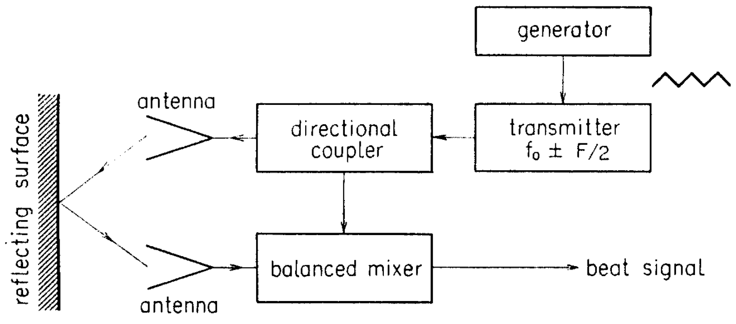

FIG. 1. Basic composition of FM radio altimeter.

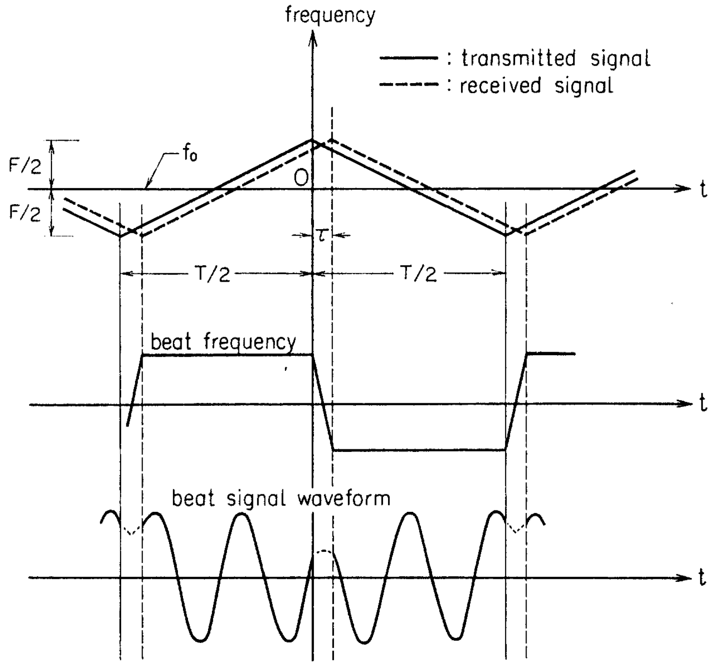

FIG. 2. Instantaneous frequencies and beat signal waveform.

f_0: the carrier frequency,
F: the maximum frequency deviation,
T: the cycle time of modulation.

In Fig. 2, τ denotes the delay time between transmission and reception, $(\tau \ll T)$. The adjacent half intervals of beat (frequency) signal, i.e. the output signal of the mixer, are mirror symmetric each other if τ is constant. The number of waves ν (containing a fraction) during a half period $T/2$ would be given;

$$\nu = F\tau = 2hF/c \qquad (1)$$

where c denotes the light velocity and h the height (the distance between antennas and reflecting surface). Here we can obtain h (the heigt information) through the measurement of ν. Hereafter we adopt numerical values; $f_0 = 4000$ MHz, $F = 100$ MHz. In this case $\nu = 1$ corresponds $h = 1.5$ m.

2-2 Counting Method and Step Error

For simplicity of processing the beat frequency is usually measured by the digital counter; the beat signal are shaped to rectagular wave and up-going zero-crossing rate should be measured. It would be easily understood, this processing is equivalent to count the up-going and down-going zero-crossing points within a half period T/2. This means that the height can be measured with the maximum error corresponding to one half of wave length of the beat signal;

$$\varepsilon_s = c/4F \qquad (0.75\,\mathrm{m}) \tag{2}$$

This type of error, inevitable to frequency counting, would be called the step error. Assuming τ is constant (and the stable transmitted and received signal), the step error cannot be eliminated even if the counting period or the measuring time could be lengthened.

The initial phase of the beat signal is decided by the phase difference of the carrier between the transmitted and the received signal; $2\pi f_0\tau = 4\pi h/\lambda_0$ (λ_0; the wave length of the carrier). The change of the carrier phase difference corresponding to the height of $\lambda_0/4$, (7.5/4 cm in our case) results in one count of increase or decrease of the counter. The step error would be caused by the change of reflecting characteristic or the faint change of height.

When the aircraft is landing with the constant vertical velocity v, the beat frequency has different values owing to the doppler frequency shift, for up-going and down-going FM periods, the difference given as $4f_0v/c$. Though the velocity v can be measured, theoretically, by the difference of the beat frequency between the two halves of the modulating period, the result is not so promising owing to the small absolute value of v/c and the step error above-mentioned. On the other hand we can exclude the effect of the doppler frequency shift when we sum up the count throughout the modulating period. Assuming the constant reflecting characteristic of the surface, the carrier phase difference would cause the step error every τ_0 seconds:

$$\tau_0 = \lambda_0/(4\,|v|) \tag{3}$$

If we are allowed to count the beat frequency for the period τ_f (τ_f means the allowable measuring time of the height), the fluctuation of the counter caused by the step error would be smoothed by the coefficient $1/\beta$, where

$$\beta = \tau_f/\tau_0 \tag{4}$$

It we adopt the value $v=0.5$ m/sec (the minimum vertical velocity at touch down), and other numerical value mentioned in section 1, τ_0 being 0.038 sec, we need $\beta=3.8$ to smooth out the step error of 0.75 m into the allowable error of 0.2 m. $\beta=3.8$ corresponding to $\tau_f=0.14$ sec, we cannot satisfy the condition (3) of section 1, i.e. we must measure the height within 0.05 sec. It should be pointed out here that the smoothing effect has no direct relation to the modulating period T and that, in case of $v=0$, there is no smoothing.

It should be also noted that the beat signal originally possesses the DC component while we are forced to use the AC amplifier after the mixer. The filtering-out of DC component results in the drift of beat signal wave that would cause some error of the frequency counting.

2-3 *Characteristics of the Received Signals*

— some experimental results —

Reflection characteristics, especially phase characteristics, influences the received signal and the beat signal. Because of the 3-dimentional movement of an aircraft at the landing phase, the reflecting surface changes continuously. As mentioned in the foregoing section phase coherency of the reflecting surface keeps the beat signal symmetric for triangular FM and its incoherency causes smoothing of the step error.

To clarify the characteristics of the reflection, experiments are made using an automobile and the concrete wall as the reflecting surface. The FM-CW altimeter mounted on the automobile is composed as shown in Fig. 1 and the received beat signal is recorded. The transmitter, shown in Fig. 3 uses the step-recovery diode which multiply the 400MHz frequency modulated signal into 4000±50 MHz transmitting signal. The modulating frequency is limited to 248 Hz from the recorder bandwidth. A pair of horn antennas are used separately as the transmitting and the receiving antennas, each having 16.7 db gain, and the coupling of the directional coupler is 13 db.

The concrete wall surface shows the reflection intensity 10 db less than that of the metal surface, which means more than 50 db better than random reflection. (The measurement is made at h=10 m.)

To measure the coherency of carrier, the autocorrelation functions of beat signal Φ (mT) are calculated from data recorded when the automobile runs on a line with antennas directed perpendicular to the wall. Calculation is made on the assumption that the phase is constant during the modulation period T and the autocorrelation function is obtained at every mT (m; integer) seconds using 4 sampled data every modulation period T. Some results are shown in Fig. 5. The autocorrelation function is composed of two main parts; the systematic phase shift due to the doppler shift of frequency, and the random phase fluctuation $\rho(mT)$,

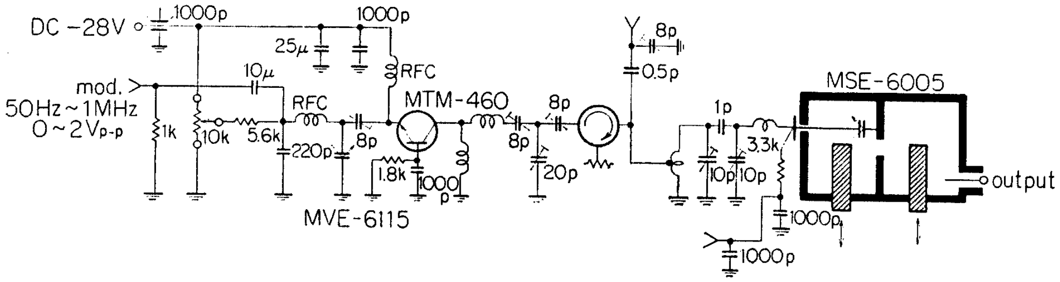

FIG. 3. Transmitter.

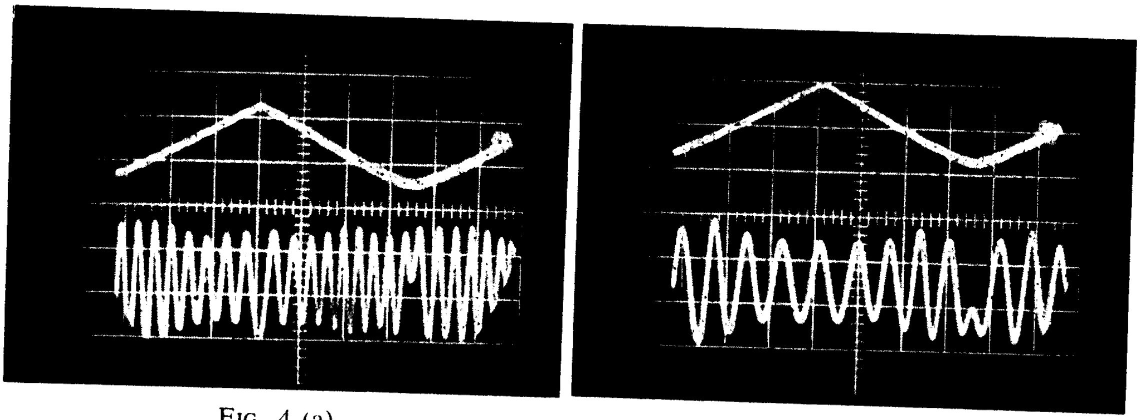

FIG. 4 (a)

FIG. 4 (b)

FIG. 4. Example of beat signal waveform: (the triangular wave denoting modulating voltage).

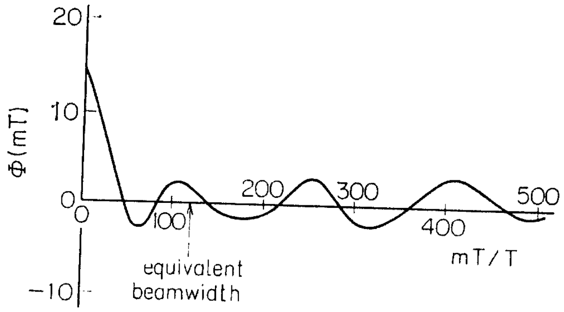

FIG. 5 (a) Autocorrelation function of beat signal: the velocity of automobil 30 km/h.

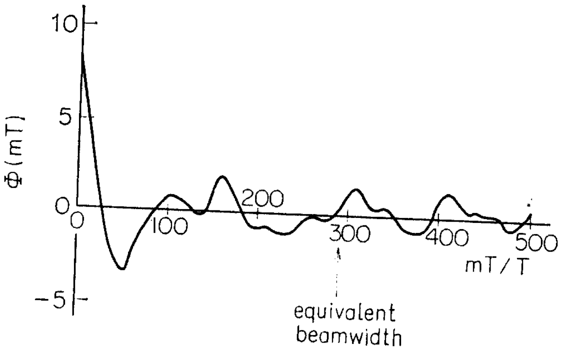

FIG. 5 (b) Autocorrelation function of beat signal: the velocity of automobile 30 km/h.

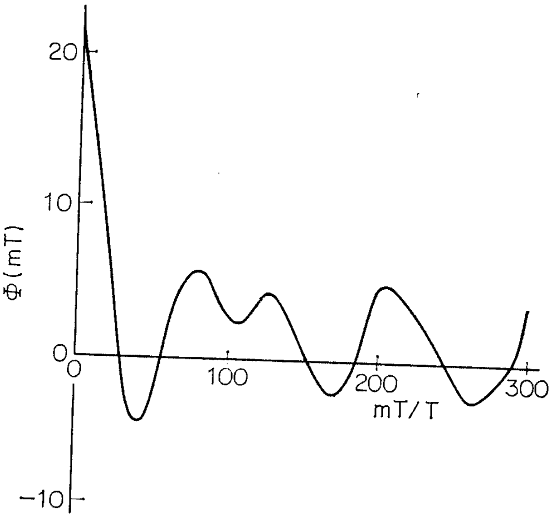

FIG. 5 (c) Autocorrelation function of beat signal: the velocity of automobile 40 km/h.

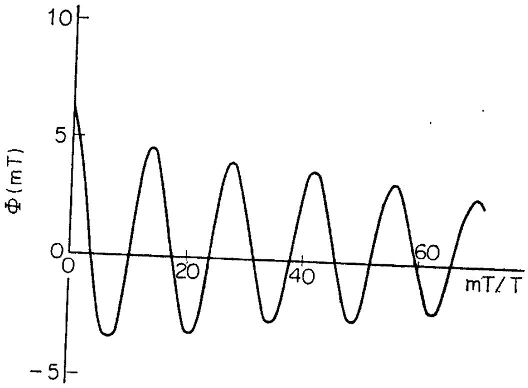

FIG. 5 (d) Autocorrelation function of beat signal: the velocity of automobile 20 km/h.

$$\Phi(mT)=\rho(mT)+\frac{A_0}{2}\cos 2\pi f_d mT+O\left(\frac{A_0}{N_1 2\pi f_d T}\cdot\frac{1}{F\tau_p}\right) \qquad (5)$$

f_d: the doppler frequency shift due to the perpendicular movement to the wall.
N_1: the total number of modulation periods used in calculation ($N_1=550\sim700$)
τ_p: the average delay time between transmission and reception

In Fig. 5, (a), (b), (c) show the almost parallel movement to the wall, and (d) shows the doppler shift evidently caused by movement of the antennas leaving the wall slowly. Our concern is in $\rho(mT)$ around the origin. We can draw an inference from Fig. 5 that the phase is coherent during $100\,T=0.35$ sec. for the parallel velocity of 40 km/h.

This result corresponds to the phase coherency during 0.05 sec. for the velocity of 220 km/h which is usual landing velocity of an aircraft. Coherency for 0.05 sec. requires more than 0.1 sec to smooth out the step error (As mentioned in section 1 the altimeter should operate within 0.05 sec).

As to the maximum measurable height, it is known through experiment, there is a limit decided by the spurious beat signal due to the mismatching in high frequency circuits, mainly between the directional coupler and the balaned mixer. The spurious beat signal is more influential than the receiver noise or the leakage between the antennas.

3. PHASE-SWITCHED FM-CW ALTIMETER

3-1 · Proposal — Phase-Switching of the Carrier

FM-Counting type of altimeter possesses some excellences, i.e. simplicity of signal processing and suppression of the spurious beat signal. On the other hand the counting type of processing leads to the step error, which limits the accuracy of measurement and degrades the minimum measurable height. Though the step error could be lowered by widening the frequency deviation of FM, from theoretical viewpoint, there is some restrictions for the airborne instrument. The maximum frequency deviation F of 100 MHz, which might be the reasonable upper limit for the airborne altimeter, leads as discussed in the foregoing sections to unsatisfactory results when combined with counting type of processing.

The trouble of step error, though inevitable to counting type of processing, exists in difficulty of smoothing. If we can perturb this error artificially around the true value of height, we can reject or diminish the error by taking average. The stable step error comes from the stable coherency of the carrier phase. We can perturb the zero-cross points of the beat signal, when we change artificially the carrier phase every modulation period. This artificial phase shift of carrier could be given, in the composition of Fig. 1, between; (1) the directional coupler and the transmitting antenna, or (2) directional coupler and the balanced mixer. Theoretically the phase shift can be regular or random from a modulation period to the next.

3-2 Regular Phase Switching

The typical example of newly proposed phase switched FM-CW radio altimeter is shown in Fig. 6. The phase shifter is chosen to be placed between the directional coupler and the transmitting antenna. The balanced mixer will be more difficult to adjust, if the phase shifter is placed between the directional coupler and the balanced mixer.

In the skelton diagram of Fig. 6, the rectanqular signal from the generator to the phase shifter is synchronized to the triangular modulation signal. The phase shifter performs $2\pi/N$ rad of phase shift at each modulation period consecutively, returning to the original phase after N period. The phase shifter is composed of l phase-switching cirduits of $2\pi/P_i$ rad ($i=0, 2, \cdots, l-1$) connected in cascade; where $l=\lfloor \log_2 N \rfloor$, ($\lfloor X \rfloor$ denoting the minimum natural number exceeding x inclusive). P_i of the i-th unit is selected to be $N/2^i$ ($i=0, 1, 2, \cdots, l-1$) The total phase shift of $2\pi k/N$ ($k=0, 1, 2, \cdots, N-1$) can be obtained from the cascade-connected units, which are controlled by the logic circuits dependently on coefficients of binary expression of k.

Because the shifted phase of carrier returns to the original phase in N steps, the frequency counting should be performed for N moduration periods and then the average zero-crossing rate should be obtained. Examples of zero-crossing positions of the beat signal are given in Fig. 7 for $N=4$ and $N=3$ assuming h is constant; the zero-cross points are shown superposed on the first half period (corresponding to the up-going portion of FM) of N modulation periods; the numerals under abscissa show the number of period where the zero-cross occurs; the figure ○ denoting the zero-cross points during up-going region and the figure × those during down-going region of the triangular wave of modulation.

Without the phase switching, the zero-cross is obtained every half cycle of the beat signal and this fact decides the maximum step error of counting method, as mentioned in sec. 2-2. We can easily understand, from Fig. 7, the maximum step error is reduced to 1/2 and 1/3 each for $N=4$ and $N=3$, compared to that without phase switching. By taking N-phase switching, in general, the step error is reduced 1/m for N: $N=2$ m (N: ever number), $N=$m (N: odd number).

It should be noted here the small height change is also reduced to 1/m that causes the carrier phase shift which results in one count increase or decrease of the fre-

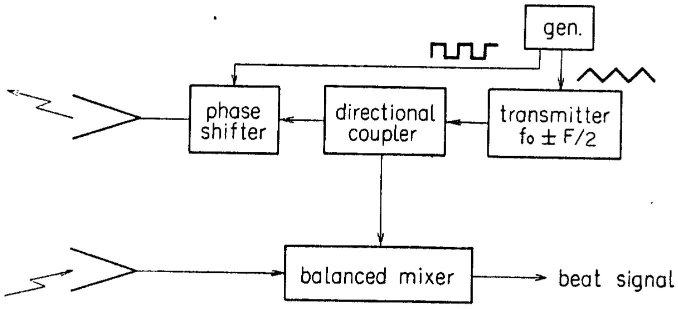

FIG. 6. Phase switched FM radio Altimeter.

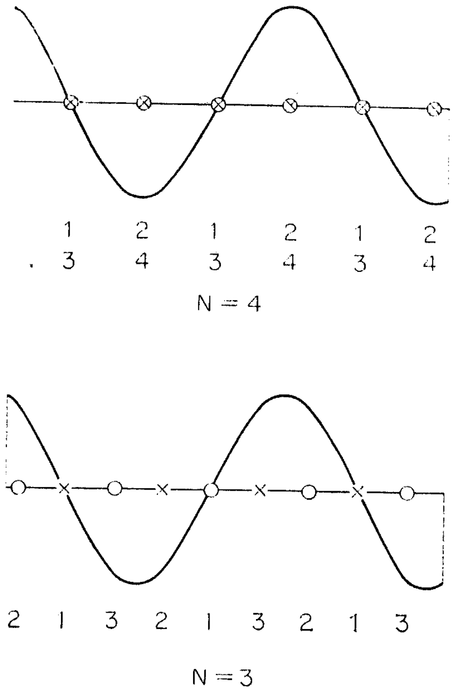

FIG. 7. Zoro-crossing positions of beat signal.

quency counter. Consequently the effect of smoothing is enhanced when the vertical velocity is present as mentioned in sec. 2-2.; we require only one m^2-th of the smoothing time because of the step error reduced to 1/m and τ_0 (eq. (3)) reduced to 1/m also. There are some desirable byproducts of the regular phase switching. The beat signal contains no DC component because of the regular phase shift and the error due to the use of AC amplifier before the counter does not exist. The effect of the spurious beat signal, that has no relation to the phase shifter with such a composition as Fig. 6, and also the effect of amplitude modulation accompanied undesirably with the frequency modulation are both diminished by smoothing for N periods.

4. EXPERIMENTS

4-1 Equipments

Effectiveness of the phase switching of carrier, discussed in sec. 3, is tested through experiments.

Experimental equipments, though not specified to airborne use, are arranged as in Fig. 8 and Fig. 9 to constitute the phase switched FM-CW radio altimeter. The phase shifter is able to select one of $0, \pi/2, \pi, 3\pi/2$ phases sequentially (N=4). The transmitter shown in Fig. 3 is used in this experiment. The main characteristics of the altimeter is listed below;

(1) the available transmitted power: 30 mw

(2) the frequency bandwidth of the receiver: 10 Hz~5 MHz (at 3 db down)

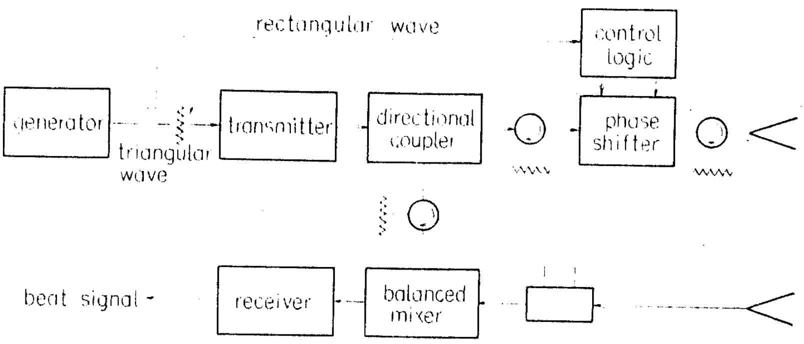

FIG. 8. Phase-switched FM-CW Altimeter.

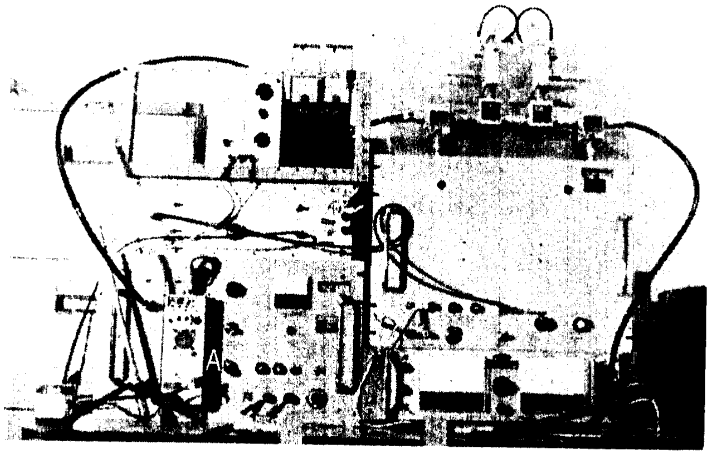

FIG. 9. Equipments. A: transmitter, B: receiver, C: generator, D: phase shifter (microwave part), E: phase shifter (driver).

(3) the phase shifter
VSWR≤ 1.2
the switching frequency $(1/T) \leq 10\,\mathrm{KH}_z$
the time constant of phase shift$\leq 5\,\mu$sec
the insertion loss≤ 1 db
the error of the phase shift: $\pm\pi/60$ rad
(4) the antenna gain: 16.7 db

4-2 Experimental Results

Some statical data are obtained first to ascertain alleviation of the step error through phase switching.

The distance between the altimeter and the reflecting surface is fixed constant to keep the stable condition of radio wave transmission, and the maximum frequency shift of FM is changed to simulate the change of distance h.

In Fig. 10 there are given examples of the beat signal waveforms. Fig. 11 shows the equivalent distance-indication; the abscissa denotes the modulating voltage of FM corresponding to the distance to be measured and on the vertical axis

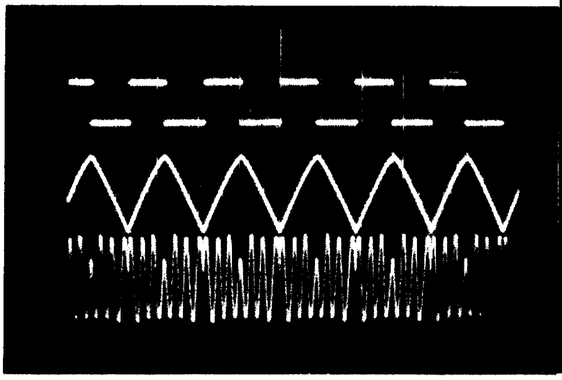

FIG. 10 (a) Signal waveforms: without phase switching.

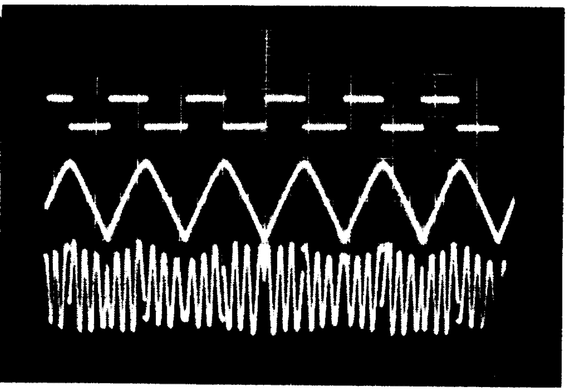

FIG. 10 (b) Signal waveforms: with phase switching.

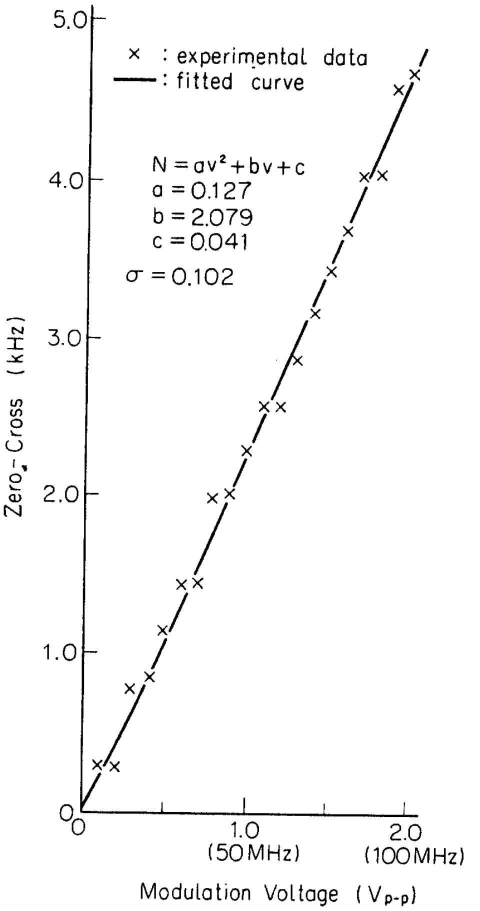

FIG. 11 (a) Equivalent distance-indication characteristics: without phase switching

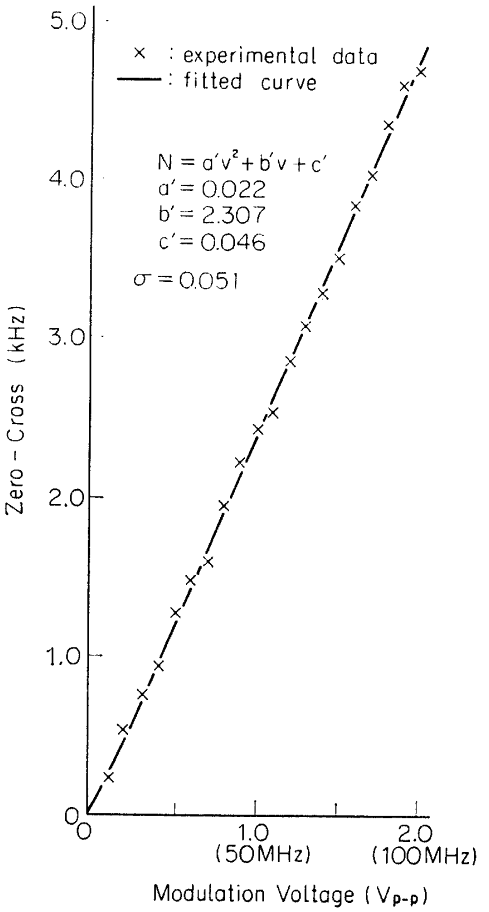

FIG. 11 (b) Equivalent distance-indication characteristics: with phase switching.

there are given indications of frequency counter, which could be transformed into the height information after normalization.

Obtained data on Fig. 11 (plotted by ×'s) would be on a line, fluctuating with the step error, if the maximum frequency deviation were in linear relation to the modulating voltage. To reject the effect of non-linearity between the modulating

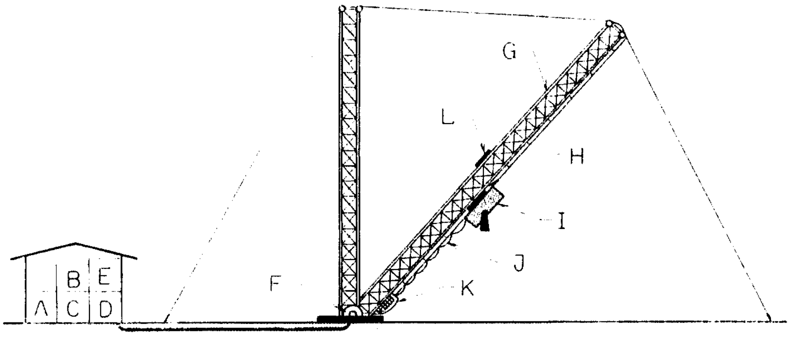

FIG. 12. Arrangement of dynamic test. A: recorder, B: controller, C: power source, D: servo-amplifier, E: analog computer F: motor, G: driving chain, H: test table, I: altimeter J: cable, K: shock absorber, L: counter balance.

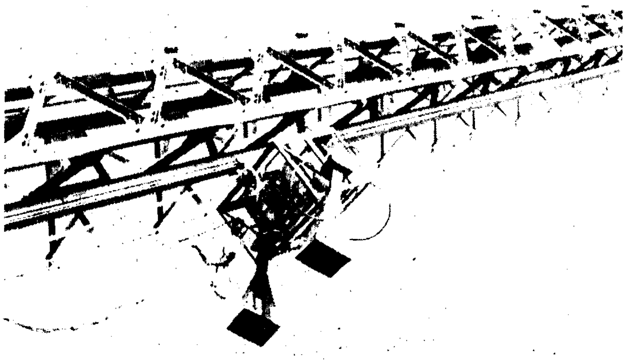

FIG. 13. Slant rail and Altimeter.

voltage and the frequency modulation, unavoidable to the real equipment, the curve of second class av^2+bv+c is fitted to the data with the minimum r.m.s. error criteria. The fitted curve is also shown in Fig. 11 with coefficients. Calculating the standard deviation σ of data from the curve, the following values are obtained; $\sigma=0.051$ with the phase switching and $\sigma=0.102$ without. This result coincides with the theoretical analysis in sec. 3, with the step error reduced to 1/2 by adopting 4-phase switching ($N=4$).

The dynamic test is performed as the second step of experiment. The altimater is arranged to run along the slant rail with antennas directed to earth, as shown in Fig. 12 and Fig. 13.

The beat signal and data showing the movement of altimeter are all recorded on a data-recorder to be processed in the laboratory. The modulating frequency f_r is selected 248 Hz throughout the experiment. The movement of altimeter, the vertical velocity v, is so controlled, simulating the landing of aircraft, as the number of modulation periods L, necessary for the transmitting and receiving phase difference to change 2π, coincides with the real case. The relation between f_r, v, and L can be given;

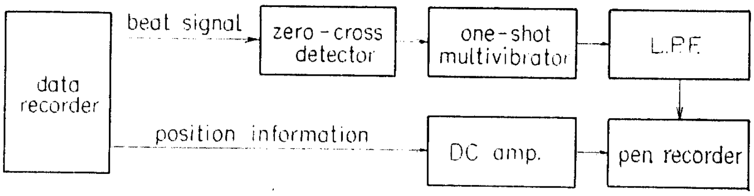

FIG. 14. Processor (used to obtain the result shown on Fig. 15).

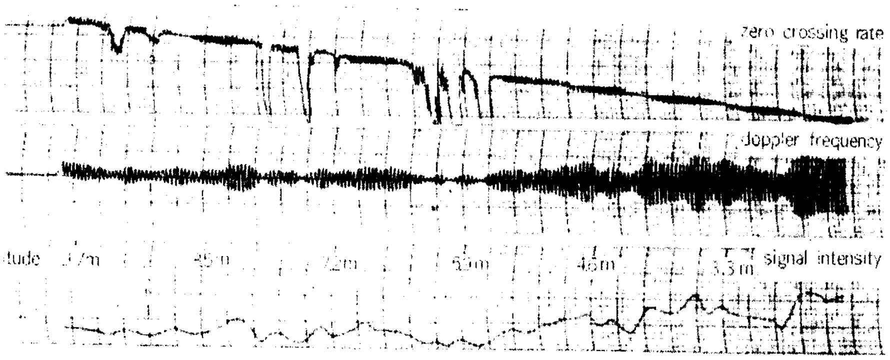

FIG. 15 (a) Example of experimental results: without phase switching.

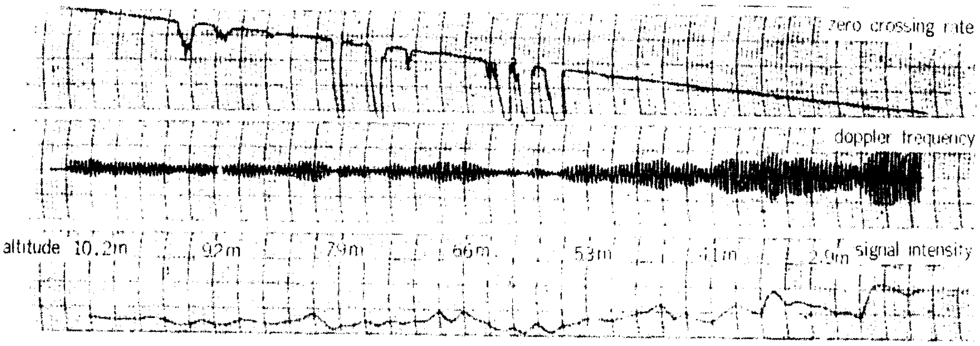

FIG. 15 (b) Example of experimental results: with phase switching.

$$L=3.75\times10^{-2}\times f_r/v \qquad (6)$$

where v in cm/sec, and the carrier frequency is 4000 MHz. Assuming 0.5~4 m/sec for the landing velocity, the simulated velocity v ranges 2.8~22.6 cm/sec. Four different values v=2.4, 12, 24, 37 cm/sec are taken in our experiment.

The recorded data are processed to obtain the height information through the circuit given in Fig. 14. The processor is devised to show the height continuously; the counter is substituted by a low pass filter (L.P.F) whose time constant is equivalent to the average counting period. One example of result is given in Fig. 15, the zero crossing rate denoting the height information. Some fault on the diagram are caused by the deterioration of receiving intensity owing to the undulation of reflecting surface. The example given is in the case $v=2.4$ cm/sec, when the smoothing constant $\beta=0.64$ (eq. (4)). With small values of β, it is recognized from Fig. 15 that the evident difference exists in the step error between two cases with the phase switching and without. Taking $v=12$, 24, 37, where $\beta \gg 1$, we cannot read the difference from such a diagram as Fig. 15, though the effect of phase switching is shown evidently by changing time constant of L.P.F.

A processor is devised which extracts the doppler information from the recorded data. The doppler information is shown, through laboratory experiments, able to be connected with the counter indication effectively to improve the height information. These results are not described in this paper.

5. CONCLUSION

Generally speaking there are two methods that reduce the step error inevitable to the FM-counter type radio altimeter. One method might be in complicated processing of the beat signal, extracting the height information not only from the zero-cross. The other is in a contrivance to the transmitting signal or the modulation, retaining the simple processing of zero-cross counting after reception. One example of the last method, the phase switching, is proposed in this paper with some analysis and experimental results.

The phase switched radio altimeter, with N-phase shift ability reduces the step error to $1/N$ (N: odd number) or $2/N$ (N: even number) through the artifical switching of phase difference between transmitting and receiving signal. This method is more effective when the altimeter has a velocity to the reflecting surface, with the resultant improvement ratio squared. The phase switching technique diminishes other types of error: the spurious beat signal due to the inner reflection can be smoothed and the AC amplifier can be used without fear of the DC level shift.'

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