Report 1878-2

REPORT

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Investigation of	Tracking, Receiving, Recording and Analysis of Data from Echo Satellite
Subject of Report	Determination of a Pulse Train to Detect the Surface Characteristics of Echo II
Submitted by	T. Suzuki Antenna Laboratory Department of Electrical Engineering
Date	31 December 1964

NOTATION

R = Radius of Echo II

$e_i(f)$ = incident wave

$e_r(f)$ = reflected wave

$e_o(f)$ = output of "the matched filter" in receiver

c = velocity of light

f_o = carrier frequency of the transmitted wave

(x, y, z) = rectangular coordinates with the origin at the center of Echo II and with the z axis of the same of rotation of Echo II

(R, θ, ϕ) = polar coordinate expression of (x, y, z)

ΔT = apparent time delay in the wave reflected from a point on the surface, measured by the difference between $p(\theta, \phi)$ and the point on Echo II which is nearest the transmitter, i.e.,

$$\Delta T = \frac{2R}{c} (1 - \sin\theta \cdot \cos\phi)$$

Δf = apparent doppler frequency in the reflected waves, i.e.,

$$\Delta f = \frac{2f_o}{c} \Omega R \sin\theta \cdot \sin\phi$$

$|X(\theta, \phi, f_d, T_d)|$ = ambiguity function of the output of a filter which is designed to match the reflected wave from a point, $p(\theta, \phi)$ of the surface.

ABSTRACT

A possible waveform for measuring surface characteristics of Echo II is described.

It is assumed in this paper that we use a monostatic radar system, and that both transmitter and receiver are located on the x axis.

The result shows that the wave is realizable, although requiring wide transmitter and receiver bandwidths.

CONTENTS

DETERMINATION OF A PULSE TRAIN TO DETECT THE SURFACE CHARACTERISTICS OF ECHO II

I. DETERMINATION OF THE TRANSMITTED WAVEFORM

Suppose a pulse train (Fig. 1) is transmitted. The wave reflected from a strip on the surface (Fig. 2) has both some given doppler shift, Δf_{y_i}, and range delay, $\Delta T_{y_i z_j}$.

The ambiguity diagram of the output of "a matched filter" which matches the reflected signal from a point, (y_i, z_j) is shown in Fig. 3 in the form of a frequency spectrum. If only the main lobe spectral component of the received signal is allowed to pass through the receiver, high doppler resolution can be obtained, although a large amount of power from the received signal will be lost.

In order to detect surface characteristics with a resolution of (2M-1) cells along the y axis by using only the main lobe components in the signals, we may arrange channel separations as shown in Fig. 4.

The heights and widths of the main lobes of the received wave vary as a function of the reflection point, as shown by dashed lines in Fig. 4.

The transmitted wave may be selected by fitting it to the lobe at the center on the surface, since changes in the width of the lobes are very small in Echo II which is slowly rotating.

As is known, the formula for the main lobe can be written by the ambiguity function as follows:

$$(1) \qquad \left|X(\Delta f, 0, f_d, 0)\right|_{\text{main lobe}} = \left(A(\theta, \phi, R) \cdot \frac{1}{\overline{N+M} \cdot T_s'}\right)^2 \cdot \sum_{i=-\infty}^{\infty} \frac{\sin^2 \pi \left(f_d - \frac{i}{\overline{N+M} \cdot T_s'} \pm \Delta f\right) N T_s'}{\pi^2 \left(f_d - \frac{i}{\overline{N+M} \cdot T_s'} \pm \Delta f\right)}, \text{ }^1$$

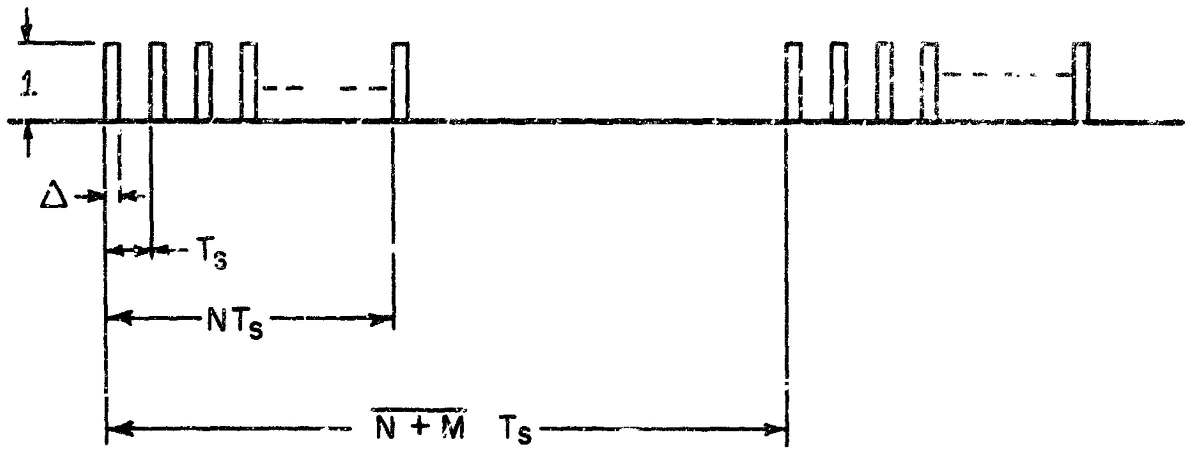


Fig. 1. Transmitter pulse trai .

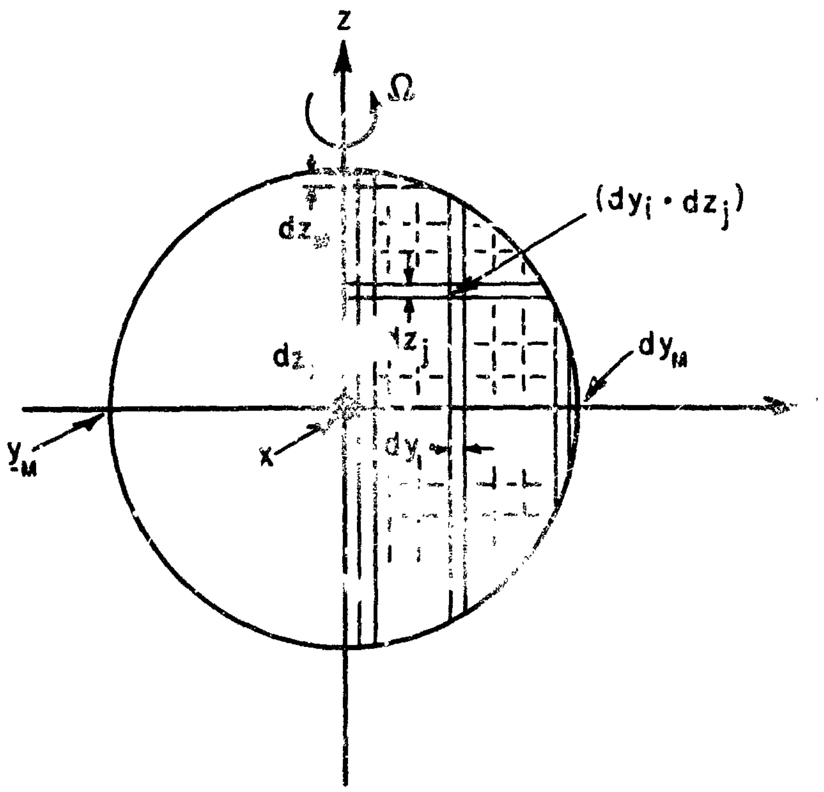


Fig. 2. Division of Echo II surface by small strips.

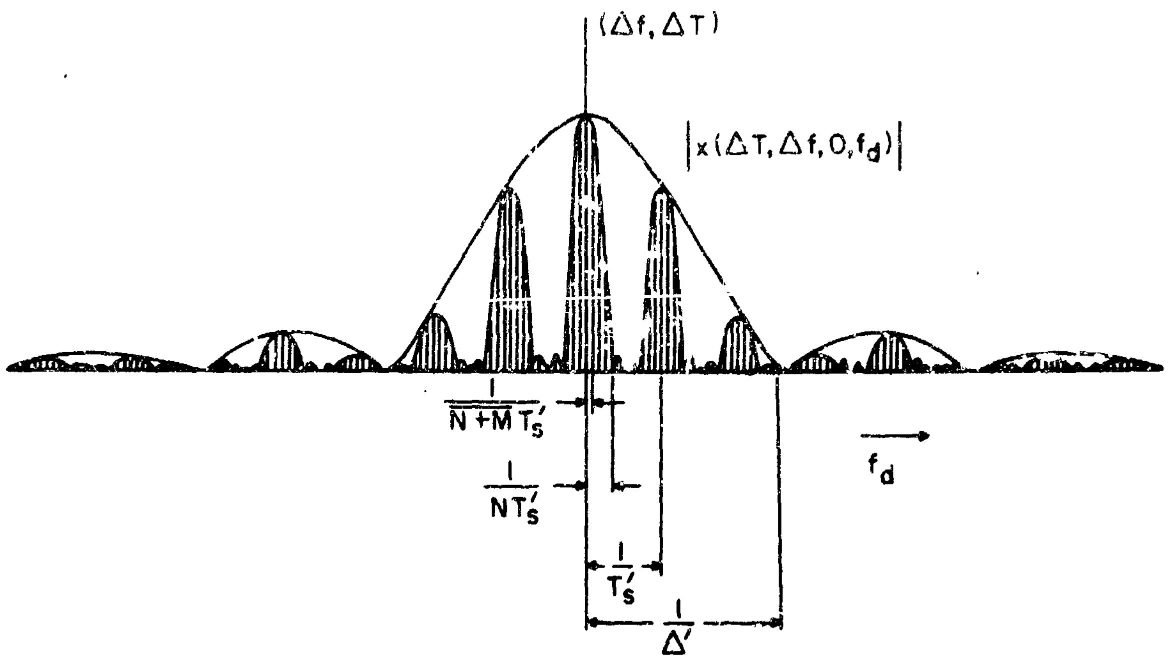


Fig. 3. Ambiguity diagram of received signal in the frequency dom-in.

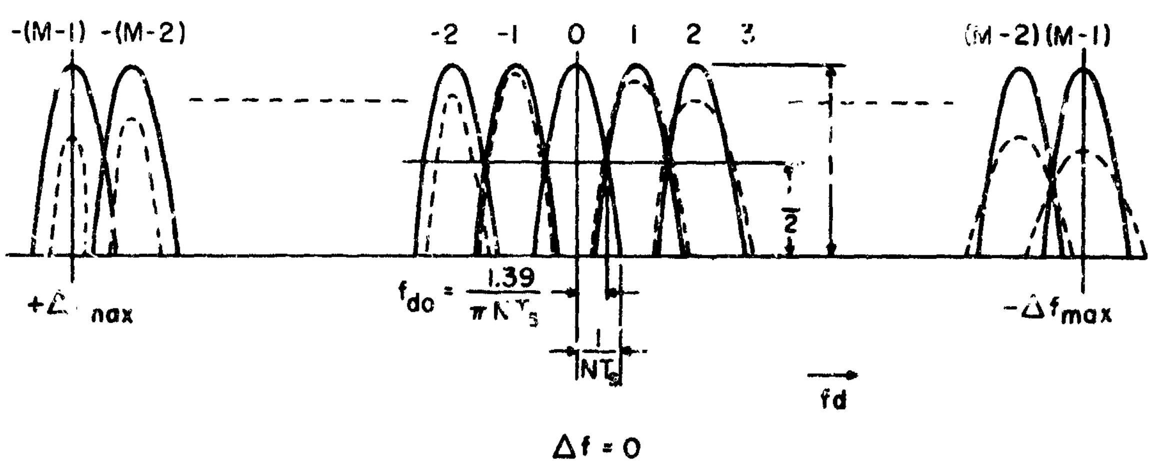


Fig. 4. Channeling in the doppler frequency range by selecting the main lobes in the received signals.

where Δf is the doppler shift in the signal reflected from a point y_i on the y axis and f_d is the difference between Δf and the frequency of the signal which is reflected from each of the other portions of the satellite. Δf becomes zero at the center of the surface of Echo II; then Eq. (2), found by substituting $\Delta f = 0$ into Eq. (1), gives the ambiguity function of the main lobe at the center of Echo II.

$$(2) \qquad |X(0, 0, f_d, o)| = \left(A(\theta, \phi, R) \cdot \frac{N}{\overline{N+M}}\right)^2 \cdot \sum_{i=-\infty}^{\infty} \frac{\sin^2 \pi\left(f_d - \frac{i}{\overline{N+M} \cdot T_s}\right) NT_s}{\pi^2\left(f_d - \frac{i}{\overline{N+M} \cdot T_s}\right)^2 (NT_s)^2}$$

The parameters of the transmitted signal; i.e., (1) the length of the pulse train (NT_s), (2) the space between each component pulse (T_s), (3) the width of a component pulse (Δ), and (4) the repetition period of the pulse train ($\overline{N+M} \cdot T_s$), are now estimated.

A. <u>The Length of the Pulse Train</u> [NT_s]

Figure 3 shows that the width of the main lobe is equal to the inverse of the length of the pulse train [NT_s], hence an increase in NT_s corresponds to a narrower main lobe and an increase in doppler resolution.

By omitting the sampling factor and normalizing the amplitude component in the Eq. (2), the expression for the main lobe at the center can be written as

$$(3) \qquad |X(0, 0, f_d, 0)| = \frac{\sin^2 \pi f_d NT_s}{(\pi f_d NT_s)^2} = \left(\frac{\sin \lambda}{\lambda}\right)^2 ,$$

where $\qquad \lambda = \pi f_d NT_s$.

Consider next the channel separation of the matched filters. The center frequencies and bandwidths of the matched filters are selected so that adjacent filters overlap at their half-power points; then

$$(4) \qquad \left(\frac{\sin \lambda_o}{\lambda_o}\right)^2 = \frac{1}{2}, \qquad \text{from which we get}$$

$$\lambda_o = 1.39;$$

(5) $\lambda_o = 1.39 = \pi f_{d_o} NT_s$, hence

(6) $$f_{d_o} = \frac{1.39}{\pi NT_s} .$$

By dividing the doppler frequency range, $+\Delta f_{max}$ through $-\Delta f_{max}$, into (2M-1) segments, corresponding to (2M-1) lobes (Fig. 4), we get

(7) $$(2M-1) \cdot \frac{1.39}{\pi NT_s} \cdot 2 = (\Delta f_{max} - (-\Delta f_{max})) = 2\Delta f_{max},$$

where

$\Delta f_{max} = \frac{2}{C} f_o \Omega R$ is the maximum doppler shift of the received signal.

Then

(8) $$(2M-1) \frac{1.39}{\pi NT_s} 2 = 2 \frac{2}{C} f_o \Omega R .$$

Rewriting Eq. (8), we get an expression for the length of the pulse train $[NT_s]$;i.e.,

(9) $$NT_s \geq (2M-1) \frac{C1.39}{2\pi f_o \Omega R} .$$

Equation (9) is written with an inequality sign to allow for some margin in channel separation, recalling the inverse relationship between the length of the pulse train and the width of the main lobe in the frequency spectrum.

B. The Space Between Component Pulses $[T_s]$

Figure 5 shows that the distance between the main lobe and the first side lobe is equal to the reciprocal of T_s, where T_s is the distance between the pulses. The matched filters must be designed to pass only the main lobes of the signal spectra, hence consideration must be given to side lobe rejection. A decrease of T_s leads to further separation of the side lobes from the main lobe. In determining the maximum value for T_s, it is necessary to consider the rejection of the side lobes of the reflected signal with maximum doppler shift. Note in Fig. 5 that the side lobe nearest the main lobe of the signals due to $+\Delta f_{max}$ is that of the signal due to $-\Delta f_{max}$, where Δf_{max} is the maximum doppler shift, i.e., the doppler shift on the y axis at the edges of Echo II. A similar relation is noted for the side lobe nearest the main lobe of the signal due to $-\Delta f_{max}$. From Fig. 5 we see that

$$(10) \quad \frac{1}{T_s'} \geqq 2\Delta f_{max} + \frac{1}{NT_s} + \frac{1}{NT_s'} = 2\Delta f_{max} + \frac{1}{NT_s}\left(1 + \frac{1}{1 \pm \frac{\Delta f_{max}}{f_o}}\right)$$

$$\doteq 2\left(\Delta f_{max} + \frac{1}{NT_s}\right) = 2\left(\frac{2}{C} f_o \Omega R + \frac{2 f_o \Omega R \pi}{1.39C(2M-1)}\right)$$

$$= \frac{4 f_o \Omega R}{C}\left(1 + \frac{\pi}{1.39(2M-1)}\right),$$

where

$$(11) \quad \frac{1}{T_s'} = \frac{1}{T_s}\left(1 \pm \frac{\Delta f_{max}}{f_o}\right)$$

and the prime sign of T_s' denotes the effect of doppler shift in frequency and is equivalent to changing the scale unit to $1/(1 \pm \Delta f/f_o)$ from unity.

In Eq. (10) we see that $\pm\Delta f_{max}$ should be $-\Delta f_{max}$. Rewriting Eq. (10)

$$(12) \quad T_s \leq \frac{C}{4 f_o \Omega R} \frac{1 - \frac{2}{C}\Omega R}{1 + \frac{\pi}{1.39(2M-1)}} .$$

The lower bound on T_s depends on the rejection of side pulses in the output of the matched filter, as shown in Fig. 6.

To obtain high range resolution from the received signal, it is necessary to detect only the output pulse with the highest peak value. If T_s is too narrow, it may be impossible to discriminate between the desired peak pulse and the side pulses of signals reflected from other points on the surface. This is analogous to the previous discussion of undesired side lobes in the frequency domain. The resulting expression

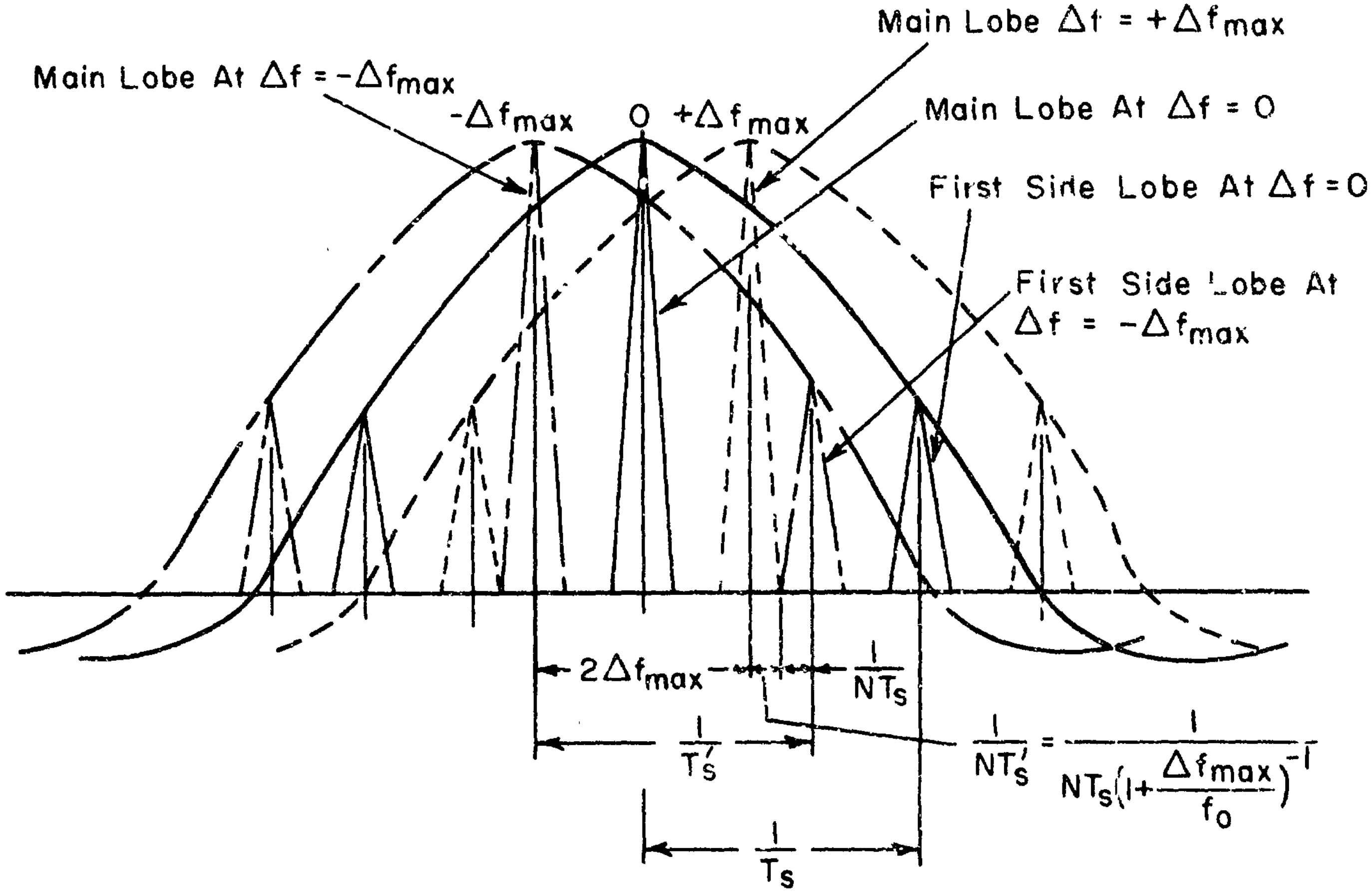


Fig. 5. Rejection of the first side lobe of the main lobe.

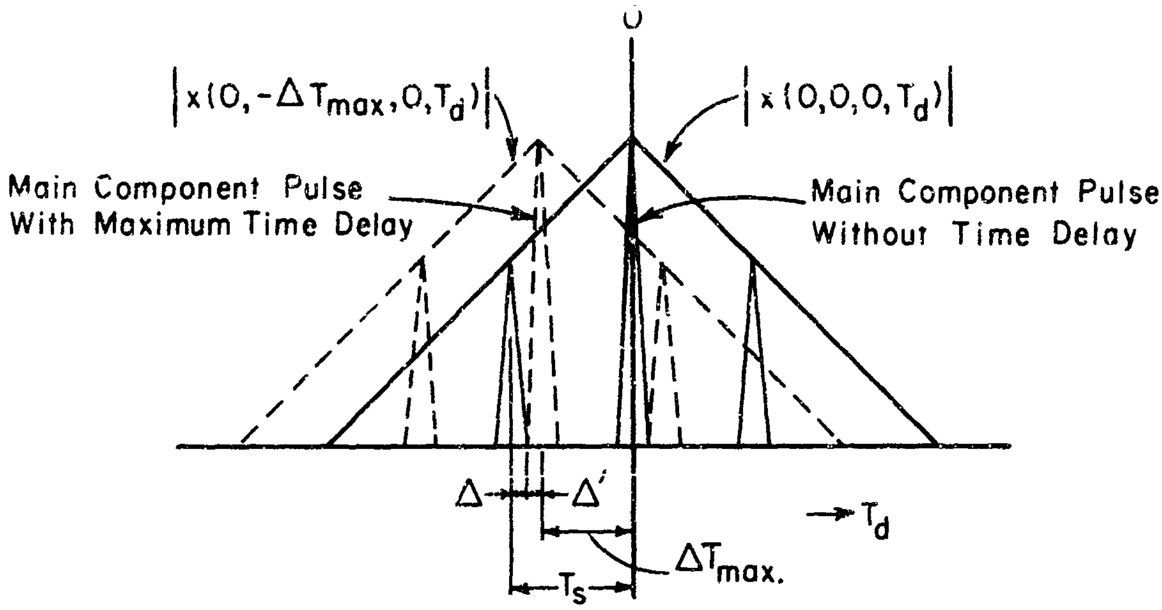


Fig. 6. Rejection of the first side pulse of the main pulse.

for the lower limit of T_s is

$$(13) \quad T_s \geq \Delta T_{max} + \Delta + \Delta' = \Delta T_{max} + \Delta\left(1 + \frac{1}{1 \pm \frac{\Delta f_{max}}{f_o}}\right) ,$$

where ΔT_{max} is the maximum range delay time of the reflected signal and is given by

$$(14) \quad \Delta T_{max} = \frac{2R}{C} .$$

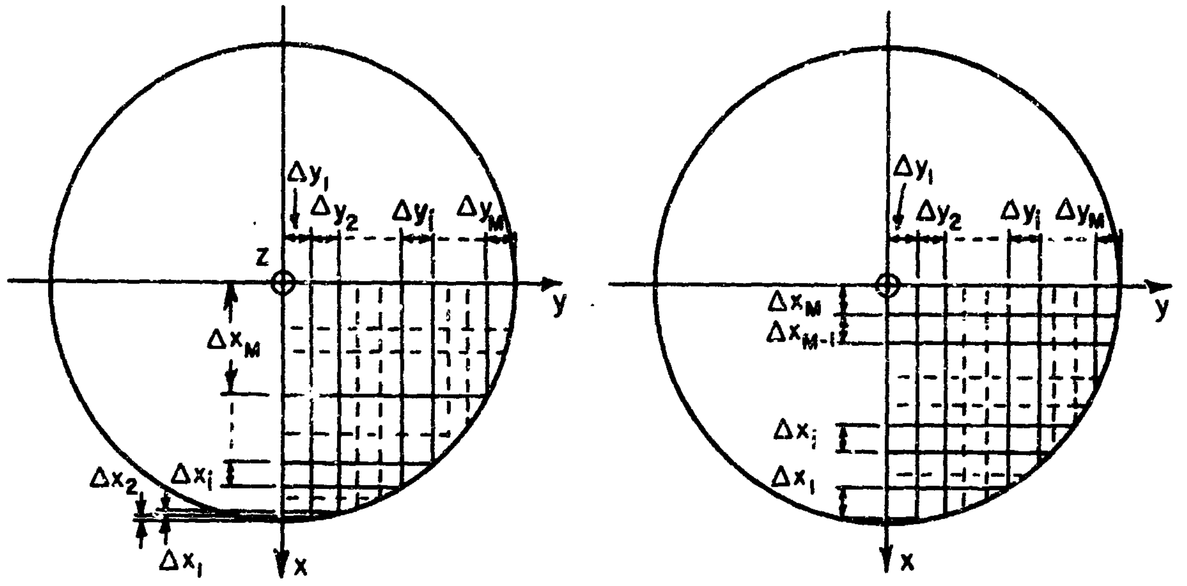
From Eq. (13) we see that $-\Delta f_{max}$ yields the desired lower bound of T_s. By combining Eqs. (12), (13), and (14), we see that T_s must satisfy the following equation:

$$(15) \quad \frac{2R}{C} + \Delta\left(1 + \frac{1}{1 - \frac{2}{C}\Omega R}\right) \leq T_s \leq \frac{C}{4 f_o \Omega R} \cdot \frac{1 - \frac{2}{C}\Omega R}{1 + \frac{\pi}{1.39(2M-1)}} .$$

C. The Width of a Component Pulse $[\Delta]$

We know from general theory of pulse radar system, that range resolution depends on the transmitted pulse width and the bandwidth in the receiver. The width of a component pulse in this system also has close relation to the range resolution of the surface characteristics.

In this paper we will treat two different processes for determining Δ from two different definitions of range resolution on a satellite surface. One of the definitions is seen in Fig. 7a; the other in Fig. 7b. Figure 7a shows that the surface is so divided into Δy_i and Δx_i such that the Δy_i



(a) Equispace Strip Along The y Axis

(b) Equispace Strip Along The x Axis

Fig. 7. Two different definitions of range resolution on the Echo II surface.

are of equal value and the Δx_i vary with i. Δx_i varies between its minimum and maximum values, Δx_{min} and Δx_{max}, respectively, with varying i:

(16) $$\Delta x_{min} \leqq \Delta x_i \leqq \Delta x_{max} \, .$$

In the x-y plane

(17) $$x_i = \sqrt{R^2 - y_i^2} \, .$$

Taking a derivative of Eq. (17) we get

$$(18) \quad \frac{\Delta x_i}{\Delta y_i} = -\frac{y_i}{x_i}$$

or

$$(19) \quad |\Delta x_i| = \left| -\frac{y_i}{x_i} \Delta y_i \right| .$$

The resolution (Δy_i) along the y axis is

$$(20) \quad \Delta y_i = \Delta y = \frac{2R}{2M-1} .$$

For Δx_i, assume its minimum value, Δx_{min}, at $y_i = \frac{\Delta y}{2}$ (Eq. (21)); and its maximum value, Δx_{max}, at $y_i = R - \Delta y$ (Eq. (22)):

$$(21) \quad |\Delta x_{min}| = \left| \frac{\frac{\Delta y}{2}}{\sqrt{R^2 - \left(\frac{\Delta y}{2}\right)^2}} \cdot \Delta y \right| ;$$

$$(22) \quad |\Delta x_{max}| = \left| \frac{(R-\Delta y)\Delta y}{\sqrt{R^2 - (R-\Delta y)^2}} \right| .$$

By substituting Eqs. (21) and (22) into Eq. (16),

$$(23) \quad \left| \frac{\frac{\Delta y}{2} \Delta y}{\sqrt{R^2 - \left(\frac{\Delta y}{2}\right)^2}} \right| \leq |\Delta x_i| \leq \left| \frac{(R-\Delta y)\Delta y}{\sqrt{R^2 - (R-\Delta y)^2}} \right| .$$

From the relation of range resolution to pulse width (Fig. 8),

$$(24) \quad \frac{2\Delta x_i}{C} = \frac{\Delta}{1 \pm \frac{\Delta f_{max}}{f_o}} \qquad \text{or}$$

$$\Delta x_i = \frac{C\Delta}{2\left(1 \pm \frac{2}{C}\,\Omega R\right)} .$$

By substituting Eqs. (20) and (24) into Eq. (23), the pulse width Δ is determined as

$$\frac{R\left(\frac{2}{2M-1}\right)^2 \left(1 - \frac{2}{C}\,\Omega R\right)}{C\sqrt{1 - \left(\frac{2}{2M-1}\right)^2}} \leq \Delta \leq \frac{R\left(1 - \frac{2}{2M-1}\right)\frac{4}{2M-1}\left(1 + \frac{2}{C}\,\Omega R\right)}{C\sqrt{1 - \left(1 - \frac{2}{2M-1}\right)^2}} . \tag{25}$$

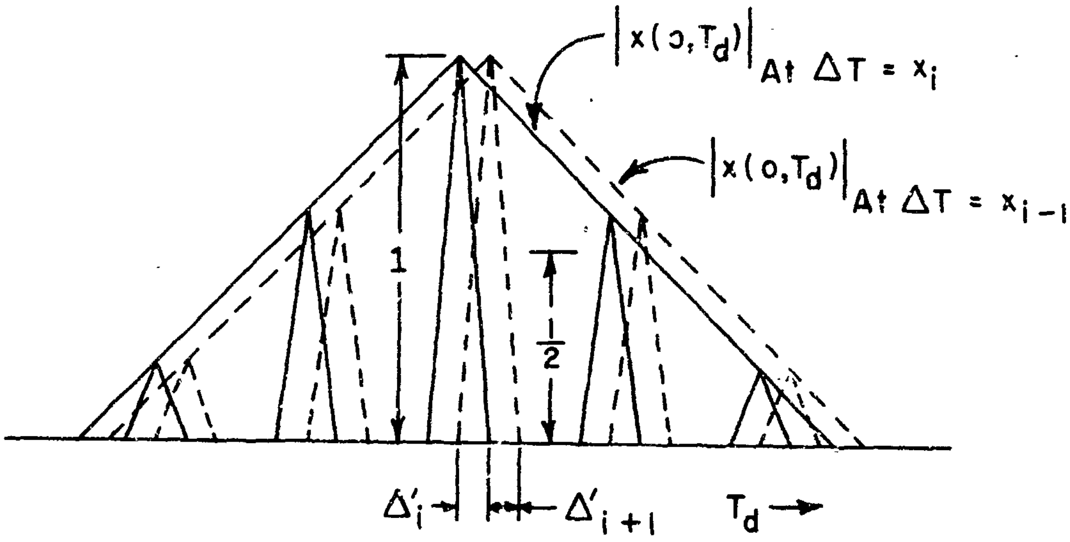


Fig. 8. Resolution between adjacent two signals in the time domain.

Figure 7(b) shows that the surface is divided by equi-spaced strips of widths Δy and Δx. From the definition of Δx, as seen in Fig. 7(b), we may estimate the range resolution which has constant value along the x axis. We define the same resolution along the y axis as Eq. (20),

$$\Delta y = \frac{2R}{2M-1} , \tag{26}$$

and we may also define it along the x axis as

$$\Delta x = \frac{2R}{2M-1} . \tag{27}$$

Changing the dimension of distance Δx to time Δ, the width of a component pulse with the doppler effect is considered as

$$(28) \quad \Delta' = \frac{2\Delta x}{C} = \frac{2}{C} \; \frac{2R}{2M-1} \quad ,$$

where

$$\Delta' = \frac{\Delta}{1 \pm \frac{\Delta f_{max}}{f_o}} = \frac{\Delta}{1 \pm \frac{2}{C}\,\Omega R} \quad .$$

From the definition of range resolution we may select $-\frac{2}{C}\,\Omega R$ for $\pm\frac{2}{C}\,\Omega r$ and write Eq. (28) with an inequality sign:

$$(29) \quad \Delta \leqq \frac{2}{C} \cdot \frac{2R}{2M-1} \left(1 - \frac{2}{C}\,\Omega R\right).$$

Equations (25) and (29) show the width of the desired transmitted pulse wave resulting from two different definitions of range resolution.

D. The Repetition Period of the Pulse Train $[\overline{N+M} \cdot T_s]$

$\overline{N+M} \cdot T_s$ can be determined by estimating the maximum distance between Echo II and the radar station. The relation between the maximum range, r_{max}, and the repetition period, $\overline{N+M} \cdot T_s$, is shown in Fig. 9; i.e.,

$$(30) \quad \overline{N+M} \cdot T_s' = \frac{2r_{max}}{C} + 2NT_s'$$

or

$$(31) \quad \overline{N+M} \cdot T_s = \frac{2r_{max}}{C} \left(1 \pm \frac{\Delta f_{max}}{f_o}\right) + 2NT_s.$$

From the definition of maximum range we get the result

$$(32) \quad \overline{N+M} \cdot T_s \geqq \frac{2r_{max}}{C} \left(1 + \frac{2}{C}\,\Omega R\right) + 2NT_s.$$

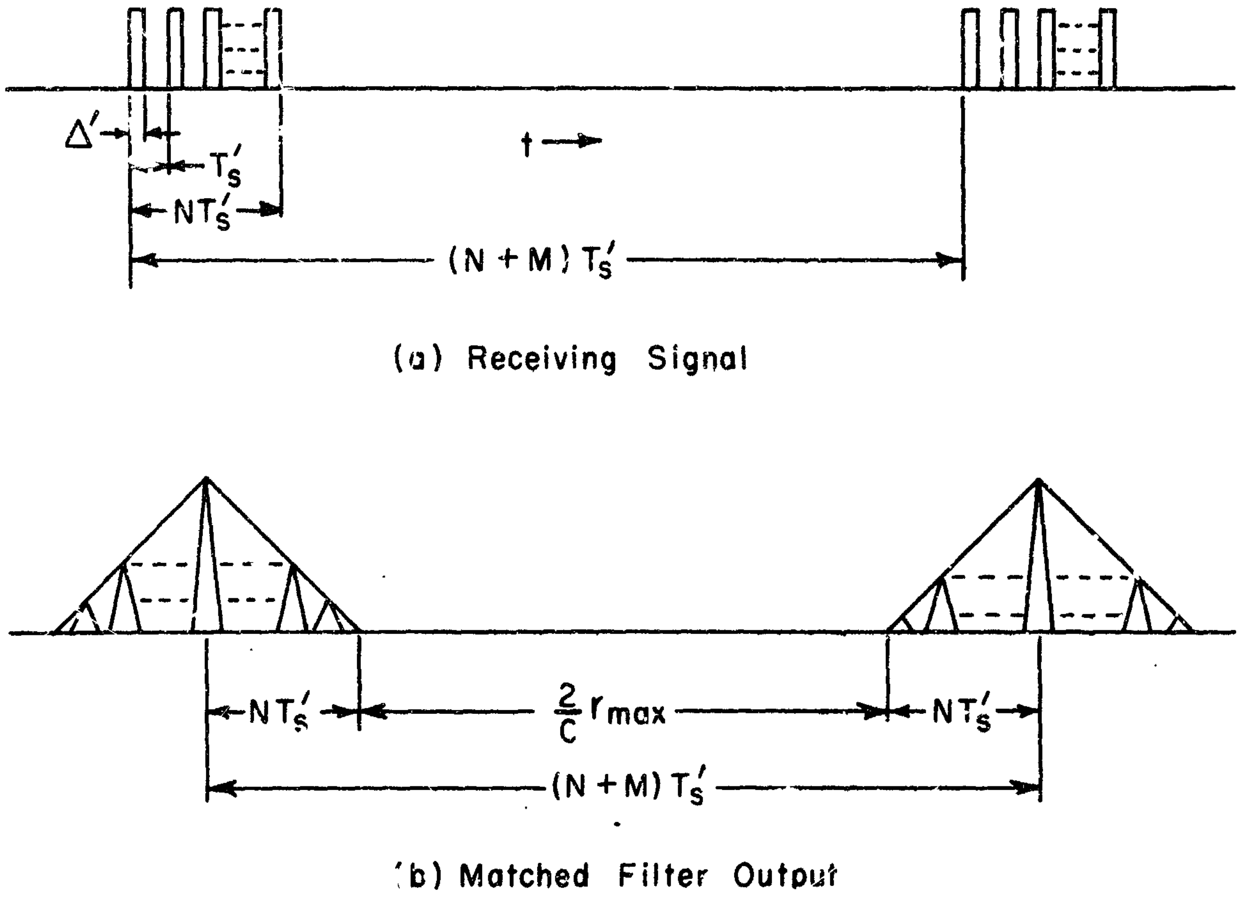


Fig. 9. Relation between maximum range, r_{max}, and repetition rate, $\overline{N+M}\cdot T_s$.

II. QUANTATIVE CALCULATION FOR ECHO II

Following are the parameters needed to calculate a suitable pulse train for detecting the surface characteristics of Echo II;

$C = 3 \times 10^8$ m/s,

$R = \frac{135'}{2} = 20.6^{m}$,

$\Omega = \frac{2\pi}{50} = 0.125^{rad}$,

$f_o = 2.270^{mc}$,

$M = 10$, and

$r_{max} = 5.000^{NM} = 9.26 \times 10^6 m$.

By putting the above parameters into Eq. (9), (15), (25), (29), and (32), we can determine the desired wave as shown below.

A. $[NT_s]$: The Length of the Pulse Train

From Eq. (9),

$$\text{(33)} \quad NT_s \geqq \frac{(2M-1)1.39C}{2\pi f_0 \Omega R} = \frac{1.9\times 10\times 1.39\times 3\times 10^8}{2\times 3.14\times 2.27\times 10^9\times 1.25\times 10^{-1}\times 2.06\times 10}$$

$$\doteq 0.215 \text{ sec.}$$

B. $[\Delta]$: The Width of a Component Pulse

From Eq. (25),

$$\text{(34)} \quad \frac{R\left(\frac{2}{2M-1}\right)^2\left(1-\frac{2}{C}\Omega R\right)}{C\sqrt{1-\left(\frac{2}{2M-1}\right)^2}} \leqq \Delta \leqq \frac{R\left(1-\frac{2}{2M-1}\right)\left(\frac{4}{2M-1}\right)\left(1+\frac{2}{C}\Omega R\right)}{C\sqrt{1-\left(1-\frac{2}{2M-1}\right)^2}}$$

or

$$\frac{2.06\times 10\times\left(\frac{2}{19}\right)^2\times\left(1-\frac{2\times 1.25\times 10^{-1}\times 2.06\times 10}{3\times 10^8}\right)}{3\times 10^8\sqrt{1-\left(\frac{2}{19}\right)^2}}$$

$$\leqq \Delta \leqq \frac{\left(1-\frac{2}{19}\right)^2\left(\frac{4}{19}\right)\left(1+\frac{2\times 1.25\times 10^{-1}\times 2.06\times 10}{3\times 10^8}\right)}{3\times 10^8\sqrt{1-\left(1-\frac{2}{19}\right)^2}} \;;$$

Then

$$\text{(35)} \quad 7.3\times 10^{-9}\text{ sec} \leqq \Delta \leqq 6.04\times 10^{-7}\text{ sec} \quad .$$

From Eq. (29)

(36) $$\Delta \leqq \frac{2 \cdot 2R\left(1 - \frac{2}{C}\Omega R\right)}{C(2M-1)}$$

$$= \frac{2 \times 2 \times 2.06 \times 10\left(1 - \frac{2 \times 1.25 \times 10^{-1} \times 2.06 \times 10}{3 \times 10^{8}}\right)}{3 \times 10^{8} \times 19}$$

$$\doteqdot 1.44 \times 10^{-8} \text{ sec}.$$

C. [T_s]: The Space between Component Pulses

From Eq. (15)

(37) $$\frac{2R}{C} + \Delta\left(1 + \frac{1}{1 - \frac{2}{C}\Omega R}\right) \leqq T_s \leqq \frac{C\left(1 - \frac{2}{C}\Omega R\right)}{4f_o\Omega R\left(1 + \frac{\pi}{1.39(2M-1)}\right)}$$

or

$$\frac{2 \times 2.06 \times 10}{3 \times 10^{8}} + \Delta\left(1 + \frac{1}{1 - \frac{2 \times 1.25 \times 10^{-1} \times 2.06 \times 10}{3 \times 10^{8}}}\right)$$

$$\leqq T_s \leqq \frac{3 \times 10^{8}\left(1 - \frac{2 \times 1.25 \times 10^{-1} \times 2.06 \times 10}{3 \times 10^{8}}\right)}{4 \times 2.27 \times 10^{9} \times 1.25 \times 10^{-1} \times 2.06 \times 10 \left(1 + \frac{3.14}{1.39 \times 19}\right)};$$

then

$$1.39 \times 10^{-7} + \Delta \leqq T_s \leqq 1.08 \times 10^{-2}.$$

By assuming $\Delta = 6.04 \times 10^{-7}$ sec, the result is

(38) $$7.43 \times 10^{-7} \text{ sec} \leqq T_s \leqq 1.08 \times 10^{-2} \text{ sec}.$$

D. $[\overline{N+M} \cdot T_s]$: The Repetition Period of the Pulse Train

From Eq. (32),

(39) $$\overline{N+M}\cdot T_s \geq \frac{2r_{max}}{C}\left(1 - \frac{2}{C}\ \Omega R\right) + 2NT_s,$$

$$= \frac{2\times 9.26\times 10^6 \times\left(1 - \frac{2\times 1.25\times 10^{-1}\times 2.06\times 10}{3\times 10^8}\right)}{3\times 10^8} + 2\times 2.15\times 10^{-1};$$

and

(40) $$\overline{N+M}\cdot T_s \geq 0.49^{sec} .$$

E. [N]: The Number of Pulses in a Train

From Eqs. (33) and (38),

(41) $$N = \frac{NT_s}{T_s} = \frac{2.15\times 10^{-1}}{7.41\times 10^{-7}} \sim \frac{2.15\times 10^{-1}}{1.08\times 10^{-2}} ,$$

$$= 2.9\times 10^5 \sim 2\times 10,$$

i.e.,

(42) $$2\times 10 \leq N \leq 2.9\times 10^5 .$$

F. [M]: The Space between Successive Pulse Trains in Terms of Component Pulses

From Eqs. (33) and (40)

(43) $$\frac{\overline{N+M}\cdot T_s}{NT_s} = \frac{N+M}{N} = \frac{0.49}{0.215} = 2.3$$

or

(44) $$M = N(2.3-1) = 2.2N.$$

Substituting the value of N from Eq. (42) into Eq. (44) we get

(45) $$M = 2.2 \times 2 \times 10 \sim 2.2 \times 2.9 \times 10^5$$

or

$$4.4 \times 10 \leq M \leq 6.9 \times 10^5 \; .$$

Referring to the general philosophy of radar system design, we may determine the finite values of Δ, T_s, N, and M as follows:

[Δ]--Because high range resolution depends on small values of Δ, the smallest value of Δ within physical capabilities should be chosen, i.e., $\Delta = 7.3 \times 10^{-9}$ sec.

[T_s]-- For the maximum received signal power choose the smallest possible value of T_s to provide a high duty cycle, i.e., $T_s = 7.43 \times 10^{-7}$ sec.

[N]--From Eq. (41) we see that for the smallest value of T_s we get the maximum value for N, i.e., $N = 2.9 \times 10^5$.

[M]--Similarly, from Eq. (44), when N assumes its largest value, M takes on its maximum value, i.e., $M = 6.5 \times 10^5$.

Thus the results are

(46) $$\begin{bmatrix} \Delta = 7.3 \times 10^{-9} \text{ sec} \\ T_s = 7.43 \times 10^{-7} \text{ sec} \\ N = 2.9 \times 10^5 \\ M = 6.5 \times 10^5 \end{bmatrix}$$

Besides the above considerations, it is necessary to estimate the effects of noise, jitter in the pulse repetition period of the transmitted signal, and the propagation loss of the medium. These effects are outside the scope of this paper.

III. CONCLUSIONS

This report concerns determination of a pulse train which is suitable for detecting the surface characteristics of Echo II. As shown above, the parameters of the pulse train are realizable although wide transmitter and receiver bandwidth are required.

In detecting the characteristics of Echo II it seems to be more difficult to get high range resolution than high doppler resolution, since detection of doppler shift has less stringent bandwidth requirements and can easily be accomplished by comparison with a reference frequency.

REFERENCE

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