THE ECHO RANGER
A Fault Locator for Power Cables
by
Thomas Kipling Naylor

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THE ECHO RANGER
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SUMMARY

The location of faults in low-attenuation coaxial cables and open-wire lines by the use of the echo-ranging techniques of radar prompted this investigation of a method to accurately locate faults in underground power cables. As the propagation velocity of disturbances on a smooth line or cable is constant, the time delay between the transmission of a pulse into a cable and the reception of an echo from an internal discontinuity is proportional to the distance to the discontinuity. The low inductance and high dielectric losses in power cables attenuate and distort the pulses. This distortion limits the accuracy and range of equipment which must measure time intervals to the nearest $3 \times 10^{-8}$ seconds.

Basically, the Echo Ranger consists of a portable low-voltage impulse generator combined with a timing oscillator and a delayed high-speed sweep on a commercial split-beam oscilloscope. A high-power hydrogen thyratron delivers 0.1-microsecond pulses of five kilowatts (peak) to the cable.

Although the range of the apparatus now constructed is only two miles on power cable, faults at least five miles away should be visible. The minimum resistance of a detectable series fault is about five ohms and the maximum resistance of a detectable shunt fault is about 2000 ohms. Without modification, the Echo Ranger can be used on overhead lines up to four miles long.
On a 1044-foot piece of RG8U polyethylene cable, two 100-ohm shunt faults 20.8 feet apart were located within 0.63%. On a three-conductor oil-filled lead-sheathed power cable 1389 feet long, a transformer tap 484 feet away and a joint 320 feet away were located within 1.2%.

The apparatus can be readily modified to deliver 16-kilovolt 5-megawatt (peak) pulses to initiate an arc at incipient faults. The power to hold the arc must come from a superimposed power supply such as a kenotron set or the normal line voltage.

Further refinements which increase the accuracy and range without sacrificing simplicity of operation could be applied to advantage.

T.K. Naylor,
U. B. C.
September, 1943.
THE ECHO RANGER

A Fault Locator for Power Cables.

1 INTRODUCTION

Recent work on the location of faults in low-attenuation coaxial cables and open-wire lines by using the echo-ranging techniques of radar has prompted this investigation of a method to accurately locate faults in underground power cables.

Echo-ranging depends on the constancy of the velocity of propagation of disturbances on a smooth cable. The time delays between the transmission of pulses fed into one end of the cable and the arrival of reflections from internal discontinuities are proportional to the distances between the sending end and the discontinuities. Then, if the distance to one of the discontinuities is accurately known, the locations of the remainder can be easily calculated.

Although much power cable is truly coaxial, skin effect and high dielectric losses absorb most of the high-frequency components of the pulses used in echo ranging. The resulting distortion of the pulses limits the accuracy and range of the measuring equipment.

The intermittent or steady discontinuities in the smooth cable may be junction points, open circuits, short circuits, or faults. The insulation may be carbonized and the conductor more or less burnt away at a fault.
The apparatus should be portable, rugged, sensitive, accurate, simple, and inexpensive. Provision should be made to prevent extraneous disturbances such as induced voltages on the sheath, electrochemical emf's at wet faults, or accidental energizing of the core from affecting the apparatus or the operator. If possible, the measuring currents should not destroy the evidences of the cause of the fault.

If the fault will appear only when rated voltage is applied, apparatus should be devised to locate the fault while it is arcing over.

To locate a fault within 10 feet on a 10-mile cable, a time delay of $10^{-4}$ seconds must be measured to the nearest $3 \times 10^{-8}$ seconds.
11 REVIEW OF LITERATURE

Much excellent work has been done on methods of locating cable faults. Mr. Savage recently summarized many effective methods.

In bridge or loop methods, the resistances or capacitances of an unknown length of faulted cable and a known length of good cable are compared.\(^1\)

The abrupt change in the magnetic field around the cable at a discontinuity can be detected by search coils taken along the route of the cable. Shielding by the steel armouring nullifies this method. Chopped or modulated currents fed into the cable produce a traceable magnetic field.\(^2\)

The thump produced by interrupted arcing at the fault can be heard if sensitive microphones are placed on the ground over the buried cable.\(^4\) The rumbling of traffic will swamp weak sounds.

Although portable radio receivers are sometimes used to pick up the static from the arc, the shielding effect of the sheath is appreciable.\(^5\)

---

1 See reference 27 page 580-93
2 See reference 27 page 580-93 paragraph 2.2
3 See reference 27 page 580-93 paragraph 2.3
4 See reference 3 page 82
5 See reference 11 page 132
If the lead sheath is punctured, the odour of burnt insulation permeates the soil and cable conduits near the fault.

The distance to a single fault can be determined by a method in which the linearly varied frequency of the applied sine wave is beaten against the echo. The frequency of the beat will depend on how much the transmitter frequency changed while the echo was travelling to and from the discontinuity.¹

Standing waves produced when the cable is a multiple of a quarter wavelength of the applied sinusoidal voltage provide quite a simple and accurate means of locating gross faults on long cables.²

On overhead open-wire lines and low-distortion speech or television cables, echo-ranging devices using single pulses or bursts of high-frequency oscillations have proved to be quite accurate and sensitive.³ Their rapid development during the war paralleled the evolution of sensitive radar equipment.

A method of locating faults on overhead lines by using the arrival times of echoes and re-echoes of the surges produced at a flash over has been proposed by Messrs. Stevens and Stringfield.⁴

Messrs. Margoulies and Fourmarier have used 90-kv

1 See reference 26 page 387
2 See reference 20 page 46
3 See reference 17 page 4
4 See reference 29, also reference 1 page 541
impulses to locate high-resistance faults on overhead lines.  

When the faulted section of cable has been exposed, the shunt fault can be located within one inch in ten miles by a core-to-sheath potential-difference test developed by Mr. Savage.  

The vacuum-tube voltmeter connected between the core and sheath at one end of the cable drops to zero and then reverses as the battery passes the fault.

In a somewhat less accurate method, the battery is connected to the end of the cable while the voltmeter probes are moved along the sheath.

Intermittent carbonized faults can sometimes be located if the cable is vibrated and the fault is used as a carbon microphone.

As most cable faults appear at taps, joints, manholes, or places where the earth has been disturbed, rough methods of fault locating often suffice. However, precise measurements must be made if the fault is in a length of cable buried directly in the earth or under pavement.

1 See reference 19
2 See reference 27 page 580-93 paragraph 2.5.4
3 See reference 27 page 580-93 paragraph 2.4
4 See reference 27 page 580-93 paragraph 2.8.1
III INVESTIGATION

A. Theory of Propagation.

1. General Differential Equation

Consider a short length of line $\delta x$

\[ e \frac{\partial i}{\partial t} + \frac{1}{c} \frac{\partial e}{\partial t} = -rl - \frac{1}{c} \frac{\partial i}{\partial t} \delta x \]

where resistance $r = \text{ohms per unit route length}$
inductance $L = \text{henries per unit route length}$
capacitance $C = \text{farads per unit route length}$
conductance $G = \text{mhos per unit route length}$
operator $\frac{\partial}{\partial t} = \frac{1}{c}$

\[ \delta e = -ri \delta x - L \frac{\partial i}{\partial t} \delta x \]  \( \text{1} \)

and \[ \delta i = -Ge \delta x - C \frac{\partial e}{\partial t} \delta x \] \( \text{2} \)

In the limit as \( \delta x \to 0 \)

\[ -\frac{\partial e}{\partial x} = ri + L \frac{\partial i}{\partial t} = (r + Lp)i \] \( \text{3} \)

and \[ -\frac{\partial i}{\partial x} = ge + C \frac{\partial e}{\partial t} = (g + cp)e \] \( \text{4} \)

Take \( \frac{\partial^2}{\partial x^2} \) of (3) and substitute in (4)
and \( \frac{\partial^2}{\partial x^2} \) of (4) and substitute in (3)

\[ \frac{\partial^2 e}{\partial x^2} = (r + Lp) \frac{2p}{c} i = \kappa^2 e \] \( \text{5} \)

and \[ \frac{\partial^2 i}{\partial x^2} = (r + Lp) \frac{2p}{c} i = \kappa^2 i \] \( \text{6} \)

1. See reference 6 page 97
Treat (5) and (6) as ordinary linear differential equations. Then the solutions are:

\[ e_\alpha = e^{-k_\alpha} A + e^{k_\alpha} B \]  
\[ i_\alpha = e^{-k_\alpha} C + e^{k_\alpha} D \]

Where \( A, B, C, \) and \( D \) are arbitrary functions of \( t \) alone.

\[
\lambda = \sqrt{(k_1+q_1)(q_1+q_2)} = \sqrt{lc} \sqrt{\frac{2}{c} + p} \frac{\sqrt{2}}{c} + p
\]

Substitute (7) and (8) in (5) and (4) and compare coefficients of \( e^{-k_\alpha} \) and then \( e^{k_\alpha} \)

\[
\therefore \quad C = \frac{1}{\lambda} \left( \sqrt{g_1 + q_1} \right) \frac{1}{\sqrt{g_1 + q_1}} A \]
\[ D = -\frac{1}{\lambda} \left( \sqrt{g_1 + q_1} \right) B \]

let \( \eta = \sqrt{\frac{1}{c}} \)
\[ \mu = \frac{1}{\sqrt{lc}} \]
\[ \alpha = \frac{4}{2c} + \frac{5}{2c} \]
\[ \beta = \frac{4}{2c} - \frac{5}{2c} \]
\[
\therefore \quad \lambda = \frac{1}{\mu} \sqrt{(k_1+q_1)(q_1+q_2)} = \frac{1}{\mu} \sqrt{(g+\alpha)^2 - \beta^2}
\]

Then \( e_\alpha = e^{-k_\alpha} A + e^{k_\alpha} B \)
\[ i_\alpha = \frac{1}{\eta} \left( e^{-k_\alpha} A - e^{k_\alpha} B \right) \]
2. **Pulse Shape.**

If the applied voltage is sinusoidal, the steady-state solutions of the general propagation equations result when \( f \) is replaced by \( j\omega \). By means of Fourier series, a piecewise continuous function can be expressed as a sum of sines and cosines. As \( \omega \) will be different for each term of the sum, the phase shift and attenuation of each component will not be the same along the line. As pulses are essentially discontinuous and finite, distortion will be excessive unless the frequency range is kept very narrow. The ideal pulse must also be simply produced at a high enough amplitude to override background interference.

Although the peaked wave shape of the discharge current from a condenser does not cover as narrow a band of frequencies as the error function, it can be quite simply produced at high amplitude. The wavefront is steep enough for precise measurements to be made to the toe of the pulse, yet the peak is not so badly distorted that it is unrecognizable. A narrow pulse will pass quite easily through the high-voltage capacitors which couple the apparatus to a live line.

In practice, the wave shape of the applied voltage approximates

\[
500 e^{-mt} \mathbb{1}(t)
\]

where \( m \) is about \( 6 \times 10^7 \).

The factor, \( \mathbb{1}(t) \), is used because the time of rise is about \( 10^{-8} \) seconds.
3. **Solution for an Infinite Line**

(Constant parameters)

For finite solutions of the general differential equation when \( x \to \infty, \quad B \to 0 \)

Then

\[
e_x = e^{-kx} A
\]

\[
\text{and} \quad i_x = \frac{1}{B} e^{-kx} A
\]

Applying a voltage \( E(t) \) at \( x = 0 \)

\[
e_x = e^{-kx} E(t)
\]

Let \( E(t) = E e^{-mt} \)

\[
e_x = E e^{-k \sqrt{(p+i\alpha)^2 - \beta^2}} e^{-mt} \]

\[
i_x = \frac{E}{2i} \left( k + \beta \right) \left( e^{-k \sqrt{(p+i\alpha)^2 - \beta^2}} \right) \frac{1}{\sqrt{(p+i\alpha)^2 - \beta^2}} e^{-mt} 1
\]

**OPERATOR FORMULAE**

\[
\mathcal{F} \left( e^{-bt} f(t) \right) = e^{-bt} \left( b - \beta \right) f(t) \quad \text{(shifting)}
\]

\[
\mathcal{F} \left( \frac{e^{-\sqrt{\beta^2 - \beta^2} t}}{\sqrt{\beta^2 - \beta^2}} \right) 1 = I_\beta \left( \beta \sqrt{t^2 - \gamma^2} \right) y
\]

where \( I_\gamma \) is a unit function delayed until \( t = \gamma \)

1. See reference 10 page 55
2. See reference 8 page 220
Multiply both sides of (8) by $e^{-st}$

$$e^{-st} \frac{\phi}{\sqrt{\beta^2 - \beta'^2}} e^{-\sqrt{\beta^2 - \beta'^2} t} \frac{1}{1} = e^{-st} I_o \left( \beta \frac{t^2 - \beta^2}{2} \right) 1.$$  

Apply (7) to the left side of (9) to shift $e^{-st}$. Replace $p$ by $p+s$.

$$\frac{\phi}{\sqrt{(p+s)^2 - \beta^2}} e^{-\sqrt{(p+s)^2 - \beta^2} t} \left( e^{-st} 1 \right)$$

$$= \frac{\phi}{\sqrt{(p+s)^2 - \beta^2}} e^{-\sqrt{(p+s)^2 - \beta^2} t} \left( e^{-st} 1 \right)$$

$$= \frac{\phi}{\sqrt{(p+s)^2 - \beta^2}} e^{-\sqrt{(p+s)^2 - \beta^2}} 1 = e^{-st} I_o \left( \beta \frac{t^2 - \beta^2}{2} \right) 1.$$  

Solve equation (6) by using equation (7) to shift $e^{-mt}$ to the left.

$$i_x = \frac{E}{\pi} e^{-mt} \left( \alpha - \beta + p - m \right) e^{-\frac{x}{2\sqrt{(p+\alpha-m)^2 - \beta^2}}} \frac{1}{\sqrt{(p-m)^2 - \beta^2}} 1.$$  

$$= \frac{E}{\pi} e^{-mt} \left( \alpha - \beta + p - m \right) \frac{1}{\sqrt{(p-m)^2 - \beta^2}}.$$  

Apply formula (2) to equation (14). $S = \alpha - m$ and $Y = \frac{x}{m}$

$$i_x = \frac{E}{\pi} e^{-mt} \left( 1 + \frac{\alpha - \beta - m}{p} \right) e^{-\frac{p}{m} t} \left( \beta \frac{t^2 - \frac{2\beta^2}{m^2}}{2} \right) 1.$$  

$$= \frac{E}{\pi} \left\{ e^{-mt} I_o \left( \beta \frac{t^2 - \frac{2\beta^2}{m^2}}{2} \right) \frac{1}{\pi} + (\alpha - \beta - m) e^{-mt} t \int_0^\infty I_o \left( \beta \frac{t^2 - \frac{2\beta^2}{m^2}}{2} \right) dt \right\} 1.$$  

$$= \frac{E}{\pi} \left\{ e^{-mt} I_o \left( \beta \frac{t^2 - \frac{2\beta^2}{m^2}}{2} \right) + (\alpha - \beta - m) e^{-mt} t \int_0^\infty I_o \left( \beta \frac{t^2 - \frac{2\beta^2}{m^2}}{2} \right) dt \right\} 1.$$  

For a graph of $I_o(\theta) = \int_0^\theta (\phi)$ see reference 14 page 22.
The following solution for $\varepsilon_\infty$ is based on a method outlined in reference 6, pages 100-2.

From equation (4) of the derivation of the general differential equation we have

$$\varepsilon_\infty = - \frac{1}{\beta + \gamma} \frac{\partial \varepsilon}{\partial x}$$

$$= - \frac{1}{\beta + \gamma - \beta} \frac{\partial \varepsilon}{\partial x}$$

In Equation (5) shift $\varepsilon^{-\gamma t}$ one term to the right.

$$i_x = \frac{E}{\mu c \beta + m} \varepsilon^{-\gamma t} I_0 \left( \beta \sqrt{t^2 - \frac{\omega^2}{\mu^2}} \right) \frac{I \gamma}{\beta + m}$$

$$= E \sqrt{\frac{\gamma}{\mu c}} \left( \beta + \gamma - \beta \right) \frac{1}{\beta + m} \varepsilon^{-\gamma t} I_0 \left( \beta \sqrt{t^2 - \frac{\omega^2}{\mu^2}} \right) \frac{I \gamma}{\beta + m}$$

Substitute equation (21) into equation (19)

$$\varepsilon_\infty = \frac{E}{\sqrt{\mu c}} \frac{1}{\beta + m} \frac{\partial}{\partial x} \left\{ \varepsilon^{-\gamma t} I_0 \left( \beta \sqrt{t^2 - \frac{\omega^2}{\mu^2}} \right) \frac{I \gamma}{\beta + m} \right\}$$

$$= - \frac{E \sqrt{\frac{\gamma}{\mu c}}}{\beta + m} \varepsilon^{-\gamma t} \frac{\partial}{\partial x} \left\{ I_0 \left( \beta \sqrt{t^2 - \frac{\omega^2}{\mu^2}} \right) \frac{I \gamma}{\beta + m} \right\}$$

The derivative of a product contains two derivatives (a) and (b)

(a) \( \frac{\partial}{\partial x} \left( \frac{I_x}{\beta} \right) = \frac{\partial}{\partial x} \left( \frac{I_x}{\beta} \right) \) \( \left( \frac{I_x}{\beta} \right) \) \( = - \frac{1}{\beta} \frac{\partial}{\partial t} \left( \frac{I_x}{\beta} \right) \) \( = - \frac{1}{\beta} \frac{\partial}{\partial t} \left( \frac{I_x}{\beta} \right) \)

(b) \( \frac{\partial}{\partial x} \left\{ I_0 \left( \beta \sqrt{t^2 - \frac{\omega^2}{\mu^2}} \right) \right\} = - \left[ I_1 \left( \beta \sqrt{t^2 - \frac{\omega^2}{\mu^2}} \right) \right] \left( \frac{\beta}{2 \sqrt{t^2 - \frac{\omega^2}{\mu^2}}} \right) \left( - \frac{2 \omega}{\beta^2} \right) \)

Also \( \frac{1}{\beta + m} \int f(t) = e^{-\gamma t} \left[ \int e^{\gamma t} f(t) dt + C \right] \)

Hence \( \frac{1}{\beta + m} \int f(t, x) = e^{-\gamma t} \left[ \int e^{\gamma t} f(t, x) dt + F(x) \right] \)

See reference 18 page 42
Then equations 23, 25, 26, and 28 combine to give

\[ e_x = E e^{-mt} \left[ \int e^{-(\alpha-m)t} I_0 \left( \sqrt{t^2 - \frac{x^2}{\nu^2}} \right) \left( \text{unit impulse at } t=\frac{x}{\nu} \right) \, dt \right. \]

\[ - \left. \frac{\beta \nu}{\nu^2} \int e^{-(\alpha-m)t} I_1 \left( \frac{\beta \sqrt{t^2 - \frac{x^2}{\nu^2}}}{\nu} \right) 1_{x/\nu} \, dt + F(x) \right] \]

\[ = E e^{-mt} \left( e_1 + e_2 + F(x) \right) \]

The first integrand vanishes everywhere except at \( t = \frac{x}{\nu} \)

\[ e_1 = e^{-(\alpha-m)\frac{x}{\nu}} \frac{1}{x/\nu} \]

The second integrand does not contribute until \( t = \frac{x}{\nu} \)

\[ e_2 = \frac{\beta x}{\nu} \int e^{-(\alpha-m)t} \frac{I_1 \left( \frac{\beta \sqrt{t^2 - \frac{x^2}{\nu^2}}}{\nu} \right)}{\sqrt{t^2 - \frac{x^2}{\nu^2}}} \, dt \]

As \( e^{-mt} F(x) \) is not multiplied by a unit function to cause it to vanish for \( t < 0 \), then \( F(x) = 0 \)

\[ e_x = E \left[ e^{-mt} e^{-(\alpha-m)\frac{x}{\nu}} - e^{-mt} \frac{\beta x}{\nu} \int e^{-(\alpha-m)t} I_1 \left( \frac{\beta \sqrt{t^2 - \frac{x^2}{\nu^2}}}{\nu} \right) \, dt \right] 1_{x/\nu} \]

\[ = E e^{-m(t-\frac{x}{\nu})} \left[ e^{-\alpha \frac{x}{\nu}} - e^{-m \frac{x}{\nu}} \frac{\beta x}{\nu} \int e^{(\alpha-m)t} I_1 \left( \frac{\beta \sqrt{t^2 - \frac{x^2}{\nu^2}}}{\nu} \right) \, dt \right] 1_{x/\nu} \]

For graph of \( I_1(\theta) = -\int f_1(d\theta) \) see reference 14 page 224

1. Reference 15 pages 395-7
Approximate wave shape after arrival.

Express equation (33) as a function of \( T = t - \frac{x}{v} \)

\[ E_x = e^{-mT} \left\{ e^{-\alpha x} - e^{-\frac{mx}{v}} \int_0^T \frac{e^{-\frac{1}{2} (\alpha - m) (T + \frac{x}{v})}}{\beta \sqrt{T^2 + 2T \frac{x}{v}}} dT \right\} \]

As a first approximation

\[ \frac{I_j(\theta)}{\theta} = \frac{1}{2} \quad \text{for } 0 < \theta < 2 \]

\[ E_x = E e^{-mT} \left\{ e^{-\alpha x} - e^{-\frac{mx}{v}} \left[ \frac{e^{-\frac{1}{2} (\alpha - m) (T + \frac{x}{v})}}{2 (\alpha - m)} \right] \right\} \]

\[ = E e^{-mT} \left\{ e^{-\alpha x} - \frac{\beta^2}{v^2 (\alpha - m)} \left( 1 - e^{-\alpha x} \right) \right\} \]

Normally the pulses are comparatively short, i.e., \( m \) is large and \( m > \alpha \)

\[ E_x = E e^{-\frac{\alpha x}{v}} \left\{ e^{-mT} - \frac{\beta^2}{2v (m - \alpha)} \left( 1 - e^{-\alpha x} \right) \right\} \]
Examination of Parameters.

Power cable is made up of one or more stranded copper conductors separated from one another and from the enclosing lead sheath by insulation which may be oil-or bitumen-impregnated paper, rubber, varnished cambric, or inert gas. For mechanical protection the lead sheath may be armoured with an outer layer of steel strands. To a first approximation, the cable may be considered to be coaxial. For more precise calculations, the geometrical factors determined by Simmons\(^1\) should be applied.

Ware and Reed\(^2\) give formulas for \(r, l, g,\) and \(c\) for low-frequency or direct current which is assumed to be uniformly distributed over the cross-section of each conductor. At high frequencies, skin effect and dielectric absorption losses change \(r, l,\) and \(g.\) As the permittivity is relatively independent of frequency, the capacitance can be considered constant.

\[
C = \frac{\frac{c}{2} x 10^7}{2 \ln \frac{d_2}{d_1} \ v^2}
\]

farads per meter

where \(v\) is the velocity of light, \(3 \times 10^8\) m/sec

and \(\xi\) is the relative permittivity of the insulation.

1 See reference 28

2 See reference 30 pages 10,17
As skin effect will concentrate most of the current at the outer surface of the core and the inner surface of the sheath, the self-inductance due to flux linkages in the metal conductors will be reduced. However, the flux in the insulation will still link the core. This interconductor inductance can be calculated from: 

\[ L_e = 2\mu \frac{2\pi}{k_x} \times 10^{-7} \]  henries per meter

where \( \mu \) is the relative permeability of the dielectric. For most dielectrics \( \mu \) is unity.

At high frequencies, skin effect will increase the resistance by decreasing the effective cross-section of the conductors. The variations in the resistance and self-inductance will be evaluated according to the method outlined in "Surge Phenomena".  

From solution of the equations:

\[ \nabla^2 \mathbf{E} = j\omega \mu \mathbf{I} \]

\[ \nabla \times \mathbf{E} = -j\omega \mu \mathbf{H} \]

\[ \oint \mathbf{H} \cdot d\mathbf{e} = I \]

Ramo and Whinnery\(^2\) show that, for a single conductor,

\[ \frac{\kappa + j(\omega \mu)}{\kappa_0} = \frac{j\omega}{\pi} \frac{\int (\omega \mu)^{3/2} \mathcal{E}(\omega \mu)^{3/2}}{\int (\omega \mu)^{3/2}} \]

where
- \( \kappa \) is the radius of the conductor in meters
- \( \mu = \sqrt{\omega \mu_\infty} \)
- \( \omega = 2\pi f \) radians per second
- \( \mu_\infty \) is the absolute permeability of the conductor or  4\( \pi \mu_\infty \times 10^{-7} \) henries per meter

1. See reference 6 page 122
2. See reference 25 page 212
$\rho$ is the d-c resistance in ohms of a one-meter length of the conductor.

$\rho$ is the resistivity of the conductor in meter-ohms

$\rho$ is the effective resistance in ohms per meter length of the conductor

$\ell_i$ is the internal self-inductance of the conductor in henries per meter.

For the very large values of $\omega$ encountered in surges, the Bessel functions can be approximated by formulas listed on page 157 of reference 10

$$J_0 \left( \frac{ab}{\rho} \right) = \frac{\sqrt{2\pi} ab}{\sqrt{2\pi} ab} e^{i \left( \frac{ab}{\rho} - \frac{\pi}{2} \right)}$$

$$J_1 \left( \frac{ab}{\rho} \right) = \frac{\sqrt{2\pi} ab}{\sqrt{2\pi} ab} e^{i \left( \frac{ab}{\rho} + \frac{3\pi}{2} \right)}$$

$$\frac{J_0 (\theta)}{J_1 (\theta)} = e^{-\frac{1}{2} \pi f} = \frac{1}{i}$$

$$\frac{\chi + j\omega L_i}{\chi_0} = \frac{1}{2} ab \sqrt{\frac{\mu}{\rho}} \frac{j\omega}{j\omega}$$

$$= \frac{a}{2} \sqrt{\frac{\mu}{\rho}} j\omega$$

As $j\omega$ for sinusoids and $f$ are equivalent

$$\chi + j\omega L_i = \frac{a}{2} \chi_0 \sqrt{\frac{\mu}{\rho}} j\omega$$

$$\chi + L_i f = \frac{a}{2} \chi_0 \sqrt{\frac{\mu}{\rho}} j\omega + L_i f$$

Dielectric losses in the insulation of power cables account for most of the apparent conductivity. Ordinary conduction losses increase with temperature; but at the
temperatures normally encountered, they are still very small. Mr. H.H. Race has found that the total loss per cycle in the oil used in "solid-type" cables first increases and then decreases with frequency. The frequency at which maximum loss occurs increases with temperature. The apparent gain in accuracy does not warrant the added complication of approximating an equivalent shunt conductance, for the operational equations will be solved only approximately.

If the variation in $g$ is negligible, then

$$\frac{1}{\mu} = \sqrt{\frac{2k}{\ln \frac{k_2}{k_1}}} \frac{R}{2e^2 \ln \frac{k_2}{k_1}}$$

$$= \frac{1}{c} \sqrt{\kappa}$$

<table>
<thead>
<tr>
<th>Insulation</th>
<th>$\kappa_{(average)}$</th>
<th>Velocity of propagation</th>
</tr>
</thead>
<tbody>
<tr>
<td>gas</td>
<td>1.0</td>
<td>985 ft. per $\mu$-sec</td>
</tr>
<tr>
<td>polyethylene</td>
<td>2.25</td>
<td>655</td>
</tr>
<tr>
<td>oil-filled paper</td>
<td>3.5</td>
<td>525</td>
</tr>
<tr>
<td>compound</td>
<td>3.7</td>
<td>510</td>
</tr>
<tr>
<td>varnished cambric</td>
<td>4.5</td>
<td>460</td>
</tr>
<tr>
<td>rubber</td>
<td>6</td>
<td>400</td>
</tr>
</tbody>
</table>

1 See reference 24 page 437
For eccentric single-core cables, Brown\textsuperscript{1} gives the surge impedance as:

\[ z = 60\sqrt{R_0} \cdot \text{Cosh}^{-1}\left(\frac{b^2 + a^2 - x^2}{2ab}\right) \]

\textsuperscript{1} See reference 7.
5. **Approximate Solution Including Skin Effect.**

(Jacottet Method)¹

In general, for an infinite line²

\[ E_x = e^{-k_x} E(z) \]

where

\[ k = \sqrt{(k + \mu)} (\mu + \phi) \]

From section ⁴

\[ k + \phi = \frac{a}{2} \frac{k_0}{\sqrt{k_0}} \sqrt{\phi} + k_0 \phi \]

As a first approximation, assume \( \phi \) is negligible.

Let \( u = \sqrt{k_0 \phi} \)

\[ k = \frac{u}{u_0} \left( 1 + \frac{a k_0}{2 k_0} \sqrt{\frac{u}{\phi}} \right)^{\frac{1}{2}} \]

Expand by the binomial theorem

\[ k = \frac{u}{u_0} + \frac{a k_0}{4 k_0 u_0} \sqrt{\frac{u}{\phi}} - \frac{1}{8 u_0} \left( \frac{a k_0}{2 k_0} \right) \frac{u}{\phi} + \ldots \]

For a large rate of change of \( E \) i.e., large \( \phi \), ignore all but the first two terms.

Let \( \sigma = \frac{a k_0}{4 k_0 u_0} \sqrt{\frac{u}{\phi}} \)

Then \[ E_z = E \frac{\sigma^2}{u} - \sigma^2 \sqrt{\phi} E(z) \]


2. See equation 3 of Section 3.
For
\[ E(t) = E e^{-mt} \]
\[ \epsilon_x = E e^{-\frac{\sigma x}{2}} e^{-\sigma x \sqrt{t}} e^{-mt} \]
\[ = E e^{-\frac{\sigma x}{2}} e^{-\sigma x \sqrt{t}} \frac{1}{\beta + m} \]
\[ = E e^{-\frac{\sigma x}{2}} (1 - \frac{m}{\beta + m}) e^{-\sigma x \sqrt{t}} \]
\[ = E e^{-\frac{\sigma x}{2}} (1 - \frac{m}{\beta + m}) (1 - s) e^{-\frac{\sigma x}{2 \sqrt{t}}} \]
\[ = E e^{-\frac{\sigma x}{2}} \left\{ (1 - \frac{m}{\beta + m}) \cdot \frac{1}{\beta + m} \left( 1 - s e^{-\frac{\sigma x}{2 \sqrt{t}}} \right) \right\} \]
\[ = E e^{-\frac{\sigma x}{2}} \left\{ (1 - \frac{m}{\beta + m}) \int_0^t e^{mt} (1 - s e^{-\frac{\sigma x}{2 \sqrt{t}}} dt - me^{-mt} \right\} \]

(As before, \( f(x) = 0 \))

\[ \epsilon_x = E e^{-\frac{\sigma x}{2}} \left\{ (1 - \frac{m}{\beta + m}) \cdot \frac{1}{\beta + m} \left( 1 - s e^{-\frac{\sigma x}{2 \sqrt{t}}} \right) \right\} \]
\[ = E e^{-\frac{\sigma x}{2}} \left\{ e^{-mt} - e^{-\frac{\sigma x}{2 \sqrt{t}}} + me^{-mt} \right\} \int_0^t e^{mt} \frac{\sigma x}{2 \sqrt{t}} dt \]

Now
\[ E^{-B^\lambda f(t)} = f(t+\lambda) \]

\[ \epsilon_x = E \left\{ e^{-m(t+\frac{\sigma x}{2 \sqrt{t}})} - e^{-\frac{\sigma x}{2 \sqrt{t}}} + me^{-m(t+\frac{\sigma x}{2 \sqrt{t}})} \right\} \int_0^t e^{mt} \frac{\sigma x}{2 \sqrt{t}} dt \]

1. For \(\sigma = \theta\) see reference 14 page 25.
2. Reference 10 page 199
3. Reference 10 page 146
B. Reflections

1. Theory

For a finite line closed at \( x = 0 \) by an impedance \( Z \), and at \( x = L \) by an impedance \( Z_2 \) we have \(^1\)

\[
U_j = \frac{1}{T} (e^{-kx} A + e^{kx} B)
\]

At \( x = 0 \), \( e_j = A + B = e^{-\frac{kL}{8}} (A - B) \)

At \( x = L \), \( e_j = e^{-kL} A + e^{kL} B = \frac{Z_2}{Z} (e^{-kL} A - e^{kL} B) \)

let \( \frac{kL}{8} = \beta_1 \) and \( \frac{Z_2}{Z} = \beta_2 \)

Rearranging \( \beta_1 \) \( (\beta_1 - 1) e^{-2kL} A = (\beta_1 + 1) B \)

Rearranging \( \beta_2 \) \( (\beta_1 + 1) A = E + (\beta_1 - 1) B \)

let \( \mu_1 = \frac{1 - \beta_1}{1 + \beta_1} \) and \( \mu_2 = \frac{1 - \beta_2}{1 + \beta_2} \)

Then from \( \beta_2 \), \( B = -\mu_2 e^{-2kL} A \)

\(^1\) See reference 115 page 109
\[
B = \frac{-\mu_2 e^{-k\rho} \mu_1 e^{2k\rho}}{(1 - \mu_2 / \mu_1) e^{-2k\rho}(\rho + 1)} E
\]

Then from (596)
\[
A = \frac{1}{(1 - \mu_2 / \mu_1) e^{-2k\rho}(\rho + 1)} E
\]

\[
i_x = \frac{1}{\beta} \left\{ \frac{e^{-kx} + e^{-k(2\rho-x)} \mu_2}{(1 - \mu_2 / \mu_1) e^{-2k\rho}(\rho + 1)} \right\} E
\]

\[
e_x = \frac{1}{\beta} \left\{ \frac{e^{-kx} - e^{-k(2\rho-x)} \mu_2}{(1 - \mu_2 / \mu_1) e^{-2k\rho}(\rho + 1)} \right\} E
\]

Expand denominator as \((1-\theta)^{-1} = 1 + \theta + \theta^2 + \theta^3 + \ldots\)

\[
i_x = \frac{1}{\beta} \left( e^{-kx} + e^{-k(2\rho-x)} \mu_2 \right) \left( 1 + \mu_2 / \mu_1 e^{2k\rho(\rho+1)} + \ldots \right) \frac{E}{\rho + 1}
\]

Similarly
\[
e_x = \left( e^{-kx} - e^{-k(2\rho-x)} \mu_2 \right) \left( 1 + \mu_2 / \mu_1 e^{2k\rho(\rho+1)} + \ldots \right) \frac{E}{\rho + 1}
\]

For an infinite line \(B = \infty\)

\[
e_x = \left( e^{-kx} \right) \frac{E}{\rho + 1}
\]

and \(i_x = \left( e^{-kx} \right) \frac{E}{\beta(\rho + 1)}\)

\[
\frac{e_x}{i_x} = \frac{\beta}{\gamma}
\]
The voltage and current in a finite line are sums of disturbances which have travelled successively longer distances by being reflected at the discontinuities at the ends of the line. While running on the smooth line, however, the disturbances act as if each were alone on an infinite line. This statement is apparent when it is noted that the equation for the increment in $e$ or $i$ due to the second term is of the same form as that of the infinite line except that $x$ is replaced by $(2t-x)$. As the solutions of the operational equations for the infinite line are zero before $t = \frac{x}{v}$, then the solutions of the first echo equations will be zero before $t = \frac{2t-x}{v}$.

Consequently, each echo is delayed by a time which varies directly with the total length of its route. The problem then resolves itself into producing the initial pulse and accurately timing the arrival of the echoes.

If the line continues on past the shunt impedance, then replace $Z_2$ in the above formulas by $\frac{Z_3 Z_4}{Z_3 + Z_4}$.

The input voltage to $Z_4$ will be the same as across $Z_2$, viz:

$$E_b = \frac{e^{-\frac{\mu_3}{2}}(1-\mu_3)E}{(1-\mu_3 \mu_3 e^{-2\mu_3})(\mu_3+1)}$$

where $\mu_3 = \frac{1-\rho_3}{1+\rho_3}$ and $\rho_3 = \frac{Z_3 Z_4}{Z_3 + Z_4}$.
As \[ i = \frac{E}{Z_{\text{input}}} \]
then the input current to \( Z_4 \) is

\[ i = \frac{1}{Z_4} \frac{(1-\mu_3) e^{-k_0 E}}{(1-\mu_1 \mu_3 e^{-2k_0 E})(\eta_1+1)} \]

As the denominator only adds in the multiple echoes from the sending end and \( \frac{e^{-k_0 E}}{(\eta_1+1)} \) is the voltage incident on the discontinuity, then \( (1-\mu_3) \) is the voltage reflection operator and \( (1-\mu_3) \) is the refraction or transmission operator. Tables of these operators for various circuit arrangements may be found in reference 4, page 537.
2. **Terminating Impedances**

The type of echo and the attenuation produced by reflection and refraction operators can be estimated if the operator impedances are replaced by surge impedances.

The voltage-reflection operator:

\[
(-\mu_2) = \frac{Z_2 - \beta'}{Z_2 + \beta'}
\]

If the cable is open-circuited, \( Z_2 = \infty \)

\[
(-\mu_2) = +1
\]

If the cable is short-circuited, \( Z_2 = 0 \)

\[
(-\mu_2) = -1
\]

If the cable is terminated in its surge impedance,

\[
(-\mu_2) = 0
\]

This approximation holds quite closely providing the incident pulses are of short duration.1

Hence for cable terminations less than the cable surge impedance, e.g., shunt faults or taps, the polarity of the echo will be the reverse of the incident pulse; whereas for cable terminations greater than the surge impedance, the echo will be of the same polarity. The transmitted or refracted pulse will resemble the incident pulse. For maximum efficiency of reflection, the cable should be short- or open-circuited and not terminated in its surge impedance.

Now consider a uniform cable containing a discontinuity somewhere along its length.

As \( \beta' = Z_4 \) (same type of cable)

then the voltage reflection operator

\[
(-\mu_2) = \frac{-1}{1 + 2 \frac{Z_4}{Z_2}}
\]

1 See reference 6
and the voltage refraction operator

\[
\left(1 - \frac{\mu_3}{\mu_3^*}\right) = \frac{1}{1 + \frac{\mu_3}{2\mu_3^*}}
\]

If \(\frac{\mu_3}{\mu_3^*}\) is large, then very little energy will be reflected. Hence a relatively high resistance fault may go unnoticed unless its echo is highly amplified.

If \(\frac{\mu_3}{\mu_3^*}\) is small, very little energy will be refracted past the low-impedance fault. Echoes from discontinuities beyond the fault will be doubly attenuated as they must pass the discontinuity twice in order to return to the detecting apparatus.

As the echo reflected from an open circuit is of the same polarity as the incident pulse, the voltage at the open circuit at the instant of arrival of the pulse will be double the voltage of the arriving pulse. Consequently, the most sensitive detector should present an open circuit to the cable. As the thyratron is a unilateral impedance which varies with time, the value of \(\mu\) will depend on the polarity of the incoming pulse, the voltage on the grid of the thyratron, and the deionization time of the thyratron. However, unless the shunt fault is less than several hundred feet from the sending end of the cable, the thyratron acts like a high impedance to incoming pulses.

Distribution boxes will appear as low impedances unless the total admittance of all the outgoing cables equals the admittance of the single incoming cable. As transformers are generally connected to the tap joint by a five-to ten-foot
cable, the termination first appears to be a drop in impedance. The large inductive loop between the fuses and the transformer presents a high series impedance which will give an echo even though the stray capacity of the transformer winding effectively shorts the far end of the inductive loop.

Grounding reactors between insulated sections of the sheath may have enough stray capacity to appear to short the sheath discontinuity. However, this possibility has not yet been experimentally checked.

A distant good joint is too small a discontinuity to be detected without highly sensitive apparatus. However, nearby joints or joints having a series resistance of several ohms can be detected as rises in impedance. Crushed faults should give a minute echo showing a slight decrease in impedance. However, two discontinuities close together, e.g., the junctions to good cable at both ends of a wiped joint, produce echoes of opposite polarity which partly cancel one another to leave short pips which are very quickly attenuated.

Multiple echoes from complicated distribution grids should be mapped while the cable is unfaulted. If this preliminary work has not been done, the positions of the known echoes can be calculated and compared with the oscilloscope trace to determine any discrepancies which indicate faults. Lattice diagrams proposed by L.V. Bewley¹ simplify the problem of identifying multiple echoes on lines or cables whose velocity, impedance, and attenuation vary from section to section.

¹ See reference 98 page 543
3. **Effect of Change of Velocity**

As the length of the trace on the oscilloscope screen is a function of time or \( \frac{x}{v} \), care must be taken to interpret intervals between echoes in terms of the velocity of propagation of the section of cable bounded by the echoes. If a piece of flexible 50-ohm polyethylene cable connects the apparatus to a 50-ohm rubber or varnished-cambric power cable, the reflection from the junction would be almost undetectable; yet the different velocities of propagation will compress the time-distance scale of the polyethylene cable to 75% of the scale of the power cable.

A similar phenomenon occurs when the cable sheath is not connected to the grounded sheath terminal of the Echo Ranger. The sheath then acts only as a capacitive voltage-divider between the core and ground. Consequently, most of the energy in the applied pulse travels at the velocity of light in free space until the pulse reaches the first place where the sheath is grounded. An echo from the junction will be produced because the pulse will be entering a cable from an aerial line. This change of parameters may also appear at the insulated sheath-joints sometimes used to control the induced currents which heat the sheath. Only the sending end of the sheath must be grounded, for the whole of the initial pulse is then impressed directly between the core and sheath without an intervening inductive loop between line and ground.

1 See reference page 238
When the sheaths and cores are continuous, junctions between cables having different characteristic impedances will be detectable from the polarity of the echo. A drop in impedance at the echo will be indicated when the pulse is fed in from one end of the cable, whereas a rise in impedance at the same junction will appear when the pulse is fed in from the other end of the cable. ¹

¹ See reference ¹ page 548
C. Apparatus

1. Description

Basically, the apparatus consists of a low-voltage impulse generator combined with a timing device for measuring the interval between the transmission of the initial pulse and the reception of echoes from discontinuities in the cable. The input pulse approximates a 0 by 0.1 wave which reaches a peak of about 500 volts when feeding a 50-ohm line.

The impulse generator consists of a high-power hydrogen thyratron which discharges a condenser directly into the cable. A compact 2-kv power supply recharges the condenser while the echoes are being received. (See block diagram)

The timer or marker pips and the echo pattern are compared on a Cossor double-beam oscilloscope adjusted to produce a single sweep each time a pulse is sent into the cable. As the marker pips, common sweep, and initial pulse are synchronized within 0.002 µ-sec. of one another, small parts of the trace can be expanded without affecting the relationship between the marker pips and the echoes. Hence the starting of the high-speed sweep can be delayed whenever echoes from distant parts of the cable are to be examined in detail.

The apparatus, exclusive of the oscilloscope, is 23½ inches high, 10½ inches wide, and 7½ inches deep. The weight is 36½ lb. The unit consumes 175 watts from a 115-volt 60-cycle line.

As the input impedance of a cable may be as low as 50 ohms, the coupling device must provide a high burst of current
in order to impress a pulse of a reasonably high voltage. Cathode followers are limited by low transconductance and low peak plate-current unless enormous tubes are used. Ordinary Marx-type impulse generators are too bulky for easy portability, although their high-power steep-wavefront pulses could probably be used to advantage on long cables. Mercury or argon thyatrons are too slow in ionizing to provide extremely steep-fronted pulses. Also, the deionization time is so long that the thyatrons act like a short circuit to incoming inverted echoes. The sluggishness in ionizing and deionizing has been overcome in small hydrogen thyatrons, such as the Sylvania 5C22, which can deliver into a 50-ohm load 2-microsecond pulses of 5-megawatt peak power 500 times a second.\(^1\)

In this apparatus, the 5C22 is used as a switch to discharge a small condenser into the cable. As the pulse can reach a maximum of only 80 kw with 2 kv driving it, the pulse repetition frequency was stepped up to about three kilocycles. However, as the pulses are very short - \(\frac{1}{4}\) \(\mu\)-sec. - the average current through the thyatron is only 1.7 ma. Consequently only a small high-voltage power-supply is needed.

2. **Accuracy**

On RG8U Polyethylene Coaxial Cable 1023 feet long, a single 100-ohm shunt fault 71.6 feet from the sending end appeared to be 73.6 feet away - an error of 0.2%.

On a 1044-foot piece of RG8U coaxial cable with two 100-ohm shunt faults 71.6 feet and 92.4 feet respectively from the sending end, the faults appeared to be distant 78.2 feet.

1. See reference \(12\) page 96
and 93.5 feet respectively. - (Errors of 0.63% and 0.06% respectively). Note that the faults were only 20.8 feet apart.

On a three-conductor oil-filled lead-sheathed power cable 1389 feet long, a transformer tap 484 feet from the sending end was located within 25 feet before the non-linearity of the start of the trace was realized. In a later test with improved apparatus the error was reduced to 16 feet (1.15% error).

A joint, 320 feet from the sending end gave a small echo 11 feet short of its true position.

When the oscilloscope was connected to the untapped core while the pulse generator fed the tapped core of the above power cable, the transformer appeared to be 21 feet beyond its true position.

It has not yet been determined whether the frequency variation of the marker-pip oscillator or the distortion of the echo is responsible for these errors.

3. Range

Although the 50-microsecond brightened trace limits the maximum range to two miles, the size of amplified multiple echoes indicates that faults three miles away on a five-mile cable should be readily visible. If both ends of the cable are available, the effective range could be doubled, depending on the position of the fault. Ultimately, the weak echoes from distant faults will be masked by multiple echoes from intermediate discontinuities.
4. **Circuit Mechanism**

a. Multivibrator.

The master timer is a double-pentode multivibrator which produces nearly square waves under light load without appreciably altering the period of the square waves. The screen grids of the 6AG7's ($V_1$ and $V_2$) act as the anodes of a triode multivibrator which are shielded from the power-handling plates by the grounded suppressor grids. The plate current is then almost independent of the plate voltage. The total width of the asymmetrical square waves of 52 and 285 $\mu$-sec. respectively corresponds to a repetition frequency of 2970 per second. The amplitude (peak to peak) of the output is 267 volts.

b. Trigger Network.

The pulse-shaping network for triggering the thyratron is similar to the first shock-excited stage of the cascade trigger circuit used in the Marine Type-268 Radar Set.

A negative-going square wave from $V_2$ is fed onto the grid of $V_3$ which immediately cuts off the steady plate current through the inductance $L_2$. The high inductance causes the plate voltage of $V_3$ to rise to try to keep the current constant through the coil. As the inductance has appreciable stray capacity, it begins to oscillate to produce a damped sine wave of

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1 See reference 16 page 534
2 See reference 21 Diagrams 40, 45, 47.
about 30 kc. However, the 30 mh. inductance in the grid circuit of $V_3$ received a shock when the negative-going square wave was impressed on it. (Note the resulting pip in the multivibrator output). As the natural frequency of $L_1$ is about 50 kc, the voltage across it and the grid of $V_3$ will complete the first half cycle several microseconds before the voltage across $L_2$. Consequently the grid of $V_3$ will be going positive when the plate voltage nears a maximum. The sudden flow of plate current damps out the remaining oscillations of the plate inductance. Also, as the grid is driven positive, it draws enough grid current to damp out the succeeding oscillations of the 30 mh inductance.

As the thyratron ($V_5$) requires at least $20$-ma grid current to fire it at the low plate voltage of 2 kv., a cathode follower ($V_4$) is inserted between the plate of $V_3$ and the thyratron grid. As the cathode follower is suddenly overloaded when the grid space ionizes in the thyratron, the grid of $V_4$ draws current to flatten the peak of the damped sine voltage appearing on the plate of $V_3$. The negative charge, stored on the coupling capacitors while the grids were drawing current, will hold $V_4$ and $V_5$ well below cutoff when the square wave from $V_2$ finally goes positive.

c. Thyratron.

When the thyratron ($V_5$) fires, a $0.0004$-uf condenser is suddenly discharged into the cable. As the
cable appears as a resistance of only 50 ohms, the 0.5-μh discharge circuit will be much under-damped if a smaller condenser is used.

\[ C = \frac{L}{R} \] for critical damping.

Also, the thyratron is slowly discharging the condenser while the grid plasma is ionizing. (The thyratron acts like a vacuum triode.) As a larger condenser is more slowly charged, a smaller charging resistance is needed. Hence, the small current drawn by the thyratron does not appreciably lower the voltage applied to the condenser immediately before firing. A still larger condenser takes too long to discharge and requires too large a power supply.

The amplitude of the pulse fed to the cable can be decreased by the insertion of larger filtering resistors in the high-voltage power supply.

d. Voltage Divider and Filter.

In order to provide a condenser-charging path independent of the cable, a tapped 2000-ohm metallized resistor is shunted across the cable terminals. This resistor also serves as a voltage divider to feed 50% of the initial pulse and echoes from the cable to the plates of the oscilloscope. As the input capacitance of the oscilloscope is across the lower half of the resistor, the ultrahigh-frequency components of the pulses are shunted to ground so that they cannot increase the distortion of the trace on the screen.
For weak echoes, the two-megacycle video amplifier in the Cossor oscilloscope can be used providing it is not overloaded.

(e) Beam Intensifying.

In order to black out the return trace, a 65-volt peak-to-peak (i.e. 56.5 volts above zero and 8.5 volts below) square wave from $V_1$ is fed onto the grid (lower tag) of the Cossor cathode-ray tube through a 0.01-uf 1200-volt coupling capacitor. The grid resistor is 0.1 megohm. As this square wave is going positive when the thyratron is firing, the trace showing the initial pulse and subsequent echoes is intensified. During the flyback, the square wave is going negative so that the beam is blacked out. As the wave is not truly flat-topped, the focus and brilliance vary along the sweep.

(f) Triggered Sweep.

When the self-repeating trigger voltage is short-circuited, the Puckle time base in the Cossor Model 339 oscilloscope can be started and stopped by an external trigger voltage applied to the "synch" terminal. If the "synch" terminal is driven negative, the sweep condenser is discharged and the beam flies back to the left side of the screen where it remains until the "synch" terminal is driven positive and the normal sweep begins.¹

In order to delay the start of the high-speed sweep until the echoes return from the distant parts of the cable, the square-wave trigger voltage is fed through a tapped

¹ See reference 9 page 15
four-microsecond delay line. Owing to the load of the delay line on the multivibrator, the distortion along the delay line, and the multiple echoes in the delay line, the front of the trigger pulse is toppled over so that the amplitude now varies directly with time. As the voltage to cancel the negative charge on the grid of the buffer tube in the Puckle time base is picked off the "synch". potentiometer, the "synch." is used as a vernier to vary the time at which the grid of the buffer tube is driven positive. As a total delay of 10 microseconds is obtained for the fastest sweep of 8.5 cm per μ-sec., the effective trace length is expanded to 85 cm. at 8.5 cm per μ-sec.

The whole line can be unrolled across the screen by rotating the "synch." control so that measuring of time intervals by counting the marker pips is facilitated. Either another delay line can be installed or the sweep speed can be decreased to take in faults between 1/2 mile and 2 1/8 miles distant. Hence, the device can be used to locate faults which are between five feet and two miles from the end of the cable.

(g) Marker Pips.

Marker pips are used as a means of measuring equal time intervals on the horizontal trace. With the common X sweep and double beam on the Cossor, the marker pips appear on the $Y_2$ trace simultaneously with the echo pips on the $Y_1$ trace. As the marker pips are locked in step with the initial pulse fed to the cable, any portion of the sweep can be expanded and the position of the
expanded echo can be more accurately interpolated between adjacent marker pips.

For simplicity, only one frequency of marker pip is used. The oscillator frequency of 4.45 M.C. provides pips 0.225 \mu\text{-}sec. apart. Although these pips are discrete at the low speed at which the right end of the 50 - \mu\text{-}sec. brightened trace just appears on the screen, they are only 19 mm apart on the fastest sweep where 1 mm equals 0.012 \mu\text{-}sec.

A modified Hartley oscillator overdamped during the flyback time and shock excited at the beginning of the brightened trace provides the basic marker frequency. The oscillations are damped out by a shunting triode (V_{6A}) which conducts during flyback while forcing the oscillator triode (V_{6B}) down near cutoff by means of the common cathode resistor (R_{24}). The small cathode bypass condenser (C_{14}) increases the amplitude of the first few cycles by aiding the grid coil in delaying conduction of (V_{6B}) during the first half cycle and by reducing degeneration during the succeeding cycles. The amplitude of the steady oscillations is controlled by the decoupling condenser and resistor in the common plate-supply lead. This isolating filter prevents plate-supply variations from disturbing the output frequency. The sine wave is then clipped by the asymmetrical cathode follower (V_{7A}). A second cathode-follower buffer triode (V_{7B}) drives a differentiating circuit.
which produces sharp peaks at the beginning of each discontinuity in the rectified sine wave fed from $V_7$. This peaked wave impressed on a small inductance ($L_4$) produces 25-volt rounded pips 0.03 μ-sec. wide and 0.225 μ-sec. apart. Each period is further subdivided by a parasitic oscillation of the X sweep which produces bright spots 0.03 μ-sec. apart on the traces.

By increasing the resistance of the condenser-charging circuit, the thyratron can be made to fire at only each second trigger pulse. In this way, the degree of inter-modulation of the $X_1$ and $Y_2$ voltages by the echo pulses from the $Y_1$ plates can be determined from a comparison of the non-coinciding traces of alternate sweeps both of which remain on the screen. It is found that, both before and after the cable pulse is received, the timing pulses are undisturbed. However, while the cable pulse is going negative, the timing pips are displaced about 0.03 μ-sec to the right. However, this displacement is recovered while the pulse is dropping back to zero. As this effect is not noticeable until the cable pulse has reached an amplitude of 4 mm (12 volts), the toe of the pulse is not disturbed. Hence the fraction of a timing interval immediately before the cable pulse should be compared with the preceding and not the following interval.
(h) Power Supplies.

As it was originally intended to bias one of the tubes 100 volts negatively, a 400-volt condenser-input power-supply was built. As this tube was later discarded, the extra voltage was dropped through a series resistor. This method provided an additional filter section, the condenser of which was installed in the timer chassis close to the multivibrator. The plate supply delivers 90 ma at 300 volts to the timer.

As the thyatron needed only two ma at two kv, a 1500-volt RMS oscilloscope transformer was used. The filament winding for the rectifier tube was connected internally to the plate winding, because the positive side of the output in an oscilloscope is grounded. However, in order to ground the thyatron heater to produce a negative initial pulse, the negative side of the power supply must also be grounded. An insulated 2.5-volt filament supply was available in the spare centre-tapped 5-volt filament winding on the thyatron heater transformer. A red pilot lamp lights when the high-voltage transformer is on, whereas a green pilot lamp lights when only the heaters and 300-volt supply are energized.
5. **Operation**
   
   (a) Initial Adjustment.

   After connecting the oscilloscope and the power input to the pulse generator, turn on the oscilloscope and only the top heater switch of the pulse generator. Only the green light should show. If the light is red, turn off the 2000-volt plate supply (bottom switch), otherwise the thyratron cathode will develop hot spots and soon fail. While waiting 300 seconds for the thyratron cathode to heat uniformly, adjust the oscilloscope and pulse-generator controls.

1. On the generator, turn the **Sweep Delay** to zero and the **Pulse Amplitude** to the centre.

2. On the oscilloscope, turn the **Condenser** or **coarse velocity** to number 9.

3. Turn the **Velocity** and **Amplitude** to the maximum clockwise position.

4. Turn the **Trigger** to the maximum counterclockwise position.

5. The **Sync.** control should be turned almost fully clockwise.

6. Adjust the **Focus** and **Brilliancy** controls so that the timing wave is clearly seen on the screen. Focusing is simplified if the timing wave on $Y_2$ is above the zero line of $Y_1$.

---

1 See reference 9 page 20
7. If only one trace is visible, rotate either $Y_1$- or $Y_2$-shift until the other trace floats into view.

8. Now adjust the Sync. and X-shift to get the initial part of the trace expanded at the left side of the screen.

9. Initially the pulses from the cable should be connected to $Y_1$ directly and the selector switch should be set at Plates A.C. Later on, if amplification is desired, the pulses should be fed into $A_1$ and the selector switch should be turned to 2HFY1.

10. Connect the cable to the Sheath-Core terminals by short twisted or coaxial leads containing as small an inductive loop as possible.

11. When the 5-minute heating time has elapsed, turn on the 2000-volt supply to the thyratron. The pilot light should change from green to red. Do not touch the cable leads while the 2000-volt supply is energized. A downward-going pulse should appear near the left side of the screen.

12. Now turn the Velocity control counterclockwise to compress the sweep until the total number of timing pips indicates that the total cable length appears on the screen. (Allow approximately 60 circuit-feet of cable between pips). If no irregularities appear, increase the pulse
amplitude until the open end of the cable (downward pip) is visible. For cables longer than half a mile, use the amplifiers controlled by $A_1$ and $A_2$ Gain. Do not overload the amplifiers, for the pulses will be distorted and uninterpretable. The maximum positive amplitude with the built-in video amplifiers is about half an inch.

The $Y_2$ marker pips also slightly modulate the $Y_1$ cable trace to produce regularly spaced bumps. As the magnitude of these bumps is independent of the amplified signals, no ambiguity should arise. However, to identify very weak signals, the marker-pip lead should be temporarily disconnected from $Y_2$.

If the fault is very close to the sending end of a long cable, the multiple echoes can be damped out by a 50- to 100-ohm carbon resistor connected across the cable terminals. A 100-ohm carbon resistor in series with the core of the cable will give longer pulses which are more easily interpreted when the fault is less than 50 feet away.

A small echo from a known discontinuity can be more positively identified if the cable is alternately shorted and opened at this discontinuity.

(b) Trace Expansion.

After the fault has been approximately located on the compressed sweep, the trace can be expanded for a detailed study of the echoes.
After allowing 250 circuit-feet per microsecond, set the sweep-delay switch to the desired range. Set the condenser switch to position ten. Readjust the focus and brilliancy if necessary. By turning the velocity and "sync." controls slowly clockwise, one can then expand the sweep to cover up to half a mile. For more distant faults, the X-shift and velocity controls must be turned slowly counterclockwise.

(c) Measurements.

The distances between echoes on the trace can be measured in terms of the 0.225-microsecond intervals between the timing pips appearing simultaneously on the screen. These larger intervals are further subdivided by a succession of bright and dim spots produced by a parasitic oscillation of the X sweep.

All measurements should be made to the beginning of the pulse, not the peak. If two adjacent pulses partly cancel one another, the second pulse begins where the first pulse changes slope.

As the high-amplitude negative-going pulses temporarily expand the sweep whereas positive-going pulses compress the sweep, an error of about ten feet will creep in. Although the marker pips are also distorted, they maintain the same time interval between their peaks because the oscillator
is isolated. However, just count full intervals and then compare the additional fractional interval to the immediately preceding interval.

To increase the accuracy, it is advisable to work from both ends of the cable and take the weighted mean of the two fault positions so found.

6. Sample Calculation

Refer to the photographs of the oscilloscope traces showing the echoes from a power cable. By comparing the expanded traces with the compressed trace one can see that pips 2 and 3 are badly distorted. From figure 1, echoes return almost at pips 6, 9, 11, 17, and 23. From the remaining figures (which are much more distinct on the screen than in the photos) the echoes are more closely logged.

<table>
<thead>
<tr>
<th>Echo logged at</th>
<th>Intervals from beginning</th>
<th>Calculated distance (by ratio)</th>
<th>Expected Echo known distance</th>
<th>Error</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.93</td>
<td>0</td>
<td>0 feet</td>
<td>beginning of cable</td>
<td>0 ft.</td>
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<td>5.91</td>
<td>4.98</td>
<td>314</td>
<td>Joint</td>
<td>325</td>
<td>-11 ft</td>
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<td>6.94</td>
<td>8.01</td>
<td>505</td>
<td>transformer tap</td>
<td>489</td>
<td>16</td>
</tr>
<tr>
<td>11.05(?)</td>
<td>10.12</td>
<td>638</td>
<td>Joint</td>
<td>647</td>
<td>-9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(re-echo)</td>
<td>653</td>
<td>-17</td>
</tr>
<tr>
<td>16.94</td>
<td>16.01</td>
<td>1009</td>
<td>multiple echo</td>
<td>978</td>
<td>32</td>
</tr>
<tr>
<td>23.05</td>
<td>22.12</td>
<td>139 (assumed)</td>
<td>far end of cable</td>
<td>1394</td>
<td></td>
</tr>
</tbody>
</table>

x: 1394 as 4.98: 22.12 Hence x = 314
Propagation velocity = \( \frac{2 \text{ (length)}}{(\text{intervals})(\text{time of interval})} \)

= \( \frac{2 \text{ (1394)}}{(22.12)(0.225)} \)

= 560 \text{ ft. per microsec.}

Velocity relative to light = \( \frac{560}{983.6} \)

= 56.9\%
IV DISCUSSION

A. Advantages

Although the Echo Ranger has its limitations, it possesses many desirable features:

1. Multiple steady, variable, or intermittent discontinuities can be accurately located.
2. The general nature and severity of the fault is indicated.
3. Only one end of the cable is required.
4. Only ratio and proportion are used in the simple calculations.
5. The whole line is visible for rough checking of arithmetic.
6. Known discontinuities can be used as reference points.
7. Few controls in addition to those on a moderately priced commercial oscilloscope simplify operation.
8. The measuring current will not destroy the fault.
9. As the device requires little power from a light socket, it can be run from batteries and an inverter.
10. Stable operation facilitates reading, measuring, and checking.
11. The apparatus is compact and easily carried.
12. Temperature variations should not significantly affect the accuracy.
13. The propagation velocity of surges can be easily determined.

B. Limitations

1. High-resistance shunt faults, i.e. greater than 2000 ohms, cannot be detected without additional amplifiers or flashover equipment.
2. A combined series and shunt fault equaling the surge impedance of the cable appears as an infinite line and will not produce echoes.

3. Multiple faults may be missed if they are just beyond a major fault. However, the accuracy of location of the first fault is not impaired.

4. As the lower limit for series faults is about five ohms, a poor joint may not appear.

5. A "roadmap" may be required to identify echoes from complicated networks such as distribution systems.

6. The distance between any two discontinuities, such as the ends of the cable, must be accurately known. On overhead lines, the variation in velocity is small because the dielectric is air.

C. Suggested Improvements.

Several additional problems appeared while the Echo Ranger was being developed. Further refinements of the apparatus are also necessary. A method of separating arc surges from the echo-ranging pulses when self-healing faults are being flashed over could take advantage of the longer time constant of the fault-generated surges. Overloading of the amplifiers could be prevented by a variable-gain stage which is allowed to operate at maximum sensitivity only during a controllable period of the trace. The initial pulse could be cancelled by a clipper tube or a bridge. The range and the sweep delay should be increased to handle cables up to 10 miles long and overhead lines up to 300 miles. The oscillator frequency should be stabilized by a crystal. Transient disturbances of the frequency at the beginning of the trace should be investigated. If every fifth or tenth
marker pip were increased in amplitude, highly compressed sweeps would be more easily measured. A circuit similar to the present timing oscillator would provide a circular sweep locked to the initial pulse. A delayed spiral could then be used to determine the number of complete revolutions between the arrivals of echoes. Remove the initial triode current from the cable while the thyatron is ionizing. Methods of reducing intermodulation should be investigated. A cathode follower to isolate the sweep delay-line will prevent defocusing of the trace. The hydrogen thyatron could be used instead of gaps in an accurately controlled high-voltage surge generator.

D. Preliminary Note on Flashover.

If the faults are self-healing or have a high resistance, high voltage can be applied to flash over the fault while the Echo Ranger is monitoring the cable. When this high steady d-c voltage is applied so that the echo-ranging pulse voltages add to it, the arc starts more readily. The cable will flash over at a variable time after the pulse arrives at the weak spot because of the time taken to completely ionize the flash-over path. Owing to the intermittent nature of the discharge, the ruptured oil has time to escape and be partly replaced by fresh oil. Bubble formation and release will increase the agitation. When the water vapour boils out of a wet fault, the breakdown voltage will rise until the arc is extinguished.

When the fault flashes over, the arc begins to discharge
the cable on both sides of it. Once the discharge wave reaches the sending end of the cable, the supply will begin to feed current into the cable. With a poorly-regulated power supply, the stored energy is dissipated faster than it can be replenished and the arc goes out long before the next timed pulse arrives.

If a large enough power supply is not available, high-voltage echo-ranging pulses applied while the cable is normally energized but isolated from the a-c supply by a current-limiting reactor would probably be enough to flash over a weak spot and hold the arc long enough for its position to be read off the oscilloscope screen. Complete burn-down is unnecessary as the arc should have a low enough impedance over part of each a-c cycle to give a recognizable echo.

The amplitude of the intermittent arc-discharge wave is so high that the relatively small echoes superimposed on it produce vertical lines which are too faint to be interpreted. As the arc surges are not locked to the sweep, they drift faintly across the screen leaving bright and steady the synchronized echo-ranging pulses which were sent and received while the arc was temporarily extinguished. When the arc path is approaching complete breakdown, a bright pip begins to grow on the screen indicating where the fault lies.

Multiple echoes from only the arc surges could be used to locate the faults if the resulting pattern on the
oscilloscope screen could be interpreted. Further research is needed on this aspect of fault location.
V. CONCLUSIONS

A. From Theory.

1. The beginning of the disturbance, the toe of the pulse, does not reach a point a distance \( x \) away until \( t = \frac{x}{\sqrt{lc}} \) has elapsed.

2. Current and voltage waves propagate at the same velocity.

3. At the wave front, \( \frac{e}{c} = z \).

4. After the arrival of the wave front, the shape of the wave depends on the total distance the wave travelled, the type of discontinuity from which it was reflected, and the severity of the discontinuities it passed.

5. Each echo travels as if it were alone on an infinite line.

6. The velocity of propagation varies inversely as the square root of the dielectric constant of the insulation and is sensibly independent of temperature.

7. The polarity of the echo from a total impedance lower than the surge impedance of the cable will be the reverse of the incident pulse. A negligible echo will be returned from a terminating impedance equalling the surge impedance. An impedance higher than the cable surge impedance will return an echo of the same polarity as the incident pulse.

8. For maximum efficiency of reflection, the cable should be short- or open-circuited.

9. Skin effect causes a distant echo to start apparently later than it should. However, amplification will reduce this error.
10. The attenuation is much larger in cables than in open-wire lines because the inductance is decreased without a corresponding decrease in resistance. 

11. After the initial rounding of the pulse, further distortion takes place less rapidly.

B. From Experiment.

1. The surge impedance of cables is of the order of fifty ohms.

2. The propagation velocity in oil-filled cable is approximately 560 feet per microsecond.

3. The accuracy of location of an internal discontinuity is within 0.6% on RG8U polyethylene cable and is within 1.2% on oil-filled power cable.

4. Multiple shunt faults are discernable if they are more than 30 feet apart.

5. Amplified echoes must be shown in their entirety or compared with unamplified echoes, if a particular wavefront is to be positively identified.

6. The pulse from the Echo Ranger is high enough to aid the applied steady voltage in initiating a flash-over at an incipient fault.

7. The conclusions from theory have been verified.
VI. LITERATURE CITED


26. Roberts, F.F., "New Methods for Locating Cable Faults


Vll. ACKNOWLEDGMENTS

Vancouver, B.C.,
September 10, 1948.

Dr. H.J. MacLeod, Head,
Department of Mechanical and Electrical Engineering,
University of British Columbia,
Vancouver, British Columbia.

Dear Sir:

In presenting this Thesis, I wish especially to thank Dr. Frank Noakes for his encouragement and guidance throughout the investigation.

The British Columbia Electric Railway Company Limited Research Scholarship which made the work possible was gratefully accepted.

Respectfully yours,

Thomas K. Naylor.
VIII DIAGRAMS

A. Apparatus

THE ECHO RANGER
(one ninth full size)
Oscilloscope and Pulse Generator with coaxial cable attached.

Rear view of Pulse Generator, Timer, and Power Supply.
THE ECHO-RANGER

PLATE 11

BLOCK DIAGRAM

1948
# Parts List for Echo-Ranger

## (See wiring diagram)

### RESISTORS

<table>
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<th>Ohms</th>
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### CONDENSERS

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### TUBES

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<td>6B</td>
</tr>
<tr>
<td>V₂</td>
<td>6AG7</td>
<td>6SN7-GT</td>
</tr>
<tr>
<td>V₃</td>
<td>6AG7</td>
<td>6SN7-GT</td>
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<td>V₄</td>
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<tr>
<td>V₅</td>
<td>Sylvania</td>
<td>5Y3GT/G</td>
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### INDUCTANCES

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<tr>
<th>Inductance</th>
<th>Description</th>
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<tbody>
<tr>
<td>L₁</td>
<td>30 mh iron-core R.F.C.</td>
</tr>
<tr>
<td>L₂</td>
<td>Two 85 mh iron-core R.F.C. in series</td>
</tr>
<tr>
<td>L₃</td>
<td>Hammond 10H - 150 ma</td>
</tr>
<tr>
<td>L₄</td>
<td>31 turns #148 C.E. 1/2&quot; diam. form. coil 3 1/2&quot; long.</td>
</tr>
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**Delay** 4 μ-sec. T-114 Line.

(L-147-152 incl.) War Assets -
(C-172-176 incl.) Dubin Electronics.
### B. Echoes from a Power Cable

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<th>Parameter</th>
<th>Details</th>
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</thead>
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<tr>
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<td>Lead</td>
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<tr>
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<tr>
<td>Voltage</td>
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<td>Bed</td>
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<tr>
<td>Manholes</td>
<td>All dry</td>
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<tr>
<td>Grounding</td>
<td>No reactors</td>
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<tr>
<td>Terminations</td>
<td>Open-circuited pot-heads</td>
</tr>
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1. Panoramic view (compressed sweep)

0.225-microsecond marker intervals.
2. Initial Pulse

0.225-microsecond intervals.

3. Echo from a joint

0.225-microsecond intervals.
4. Echo from the transformer tap.  
0.225-microsecond intervals.

5. Transformer-tap re-echo or an echo from a second joint.  
0.225-microsecond intervals.
6. Multiple echo reflected from sending end.  
0.225-microsecond intervals.

7. Echo from open-circuited far end of cable  
0.225-microsecond intervals.