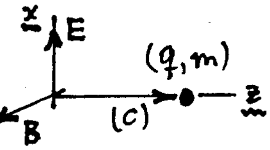
[redacted] (in class, 3 hr. limit)

Fri. 17 Mar. 1989

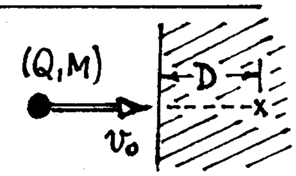
This exam is open-book, open-notes, and is worth 150 points total. For each problem, put your answer in a $\boxed{\text{box}}$ on your solution sheets. $\boxed{\text{Number}}$ your solution sheets, write your $\boxed{\text{name}}$ on sheet #1, and $\boxed{\text{staple}}$ the sheets before handing them in.



(1) [[redacted]]. A linearly polarized EM planewave impinges on an unbound charge q of mass m. The wave's electric field is: $E = E_0 \sin\omega(t - \frac{z}{c})$.

(A) Assume the field amplitude is "weak" in some sense, and calculate the average total power radiated by q (over all ∢s, etc.) during passage of the wave.

(B) Now say what you mean by "weak". How big can E_0 be before the approximation of part (A) fails? What happens in the low-frequency limit, $\omega \to 0$?



(2) [[redacted]]. A charge Q of mass M is traveling at cnst nonrelativistic velocity v_0 when it strikes a dense target. Q penetrates the target to a depth D and stops. Assume Q's deceleration in the target is ~ constant.

(A) Find the total energy $\mathcal{E}$ radiated during this event. Quote $\mathcal{E}$ in terms of (Q, D, v_0, c) only.

(B) Compare $\mathcal{E}$ with the K.E. loss ΔK during the event. About how big is $(\mathcal{E}/\Delta K)$?

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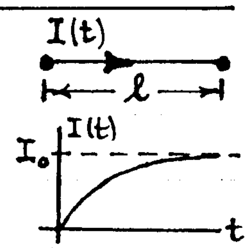
(3) [[redacted]]. For light in empty space, the phase & group velocities: $v_p = \omega/k$ & $v_g = \partial\omega/\partial k$, are both equal to c, so: $v_p v_g = c^2$.

(A) What is the most general dispersion relation $\omega = \omega(k)$ such that: $v_p v_g = \text{cnst} = v^2$ (with $v \leq c$)? What sort of medium does this dispersion relation describe?

(B) Calculate v_p & v_g as functions of k for $\omega(k)$ of part (A). Sketch a graph of v_p & v_g vs. k. At what k-value is $v_p = 2v_g$?



(4) [[redacted]]. Current $I(t)$ flows through a length ℓ of wire. $I(t) \equiv 0$ for $t<0$. Beginning at $t=0$, I is turned on gradually, over a time $\sim\tau$, so that: $I(t) = I_0(1 - e^{-t/\tau})$. Find the frequency spectrum $\sigma(\omega)$ of the radiation energy emitted. Sketch $\sigma(\omega)$ vs. ω. What happens when $\tau \to 0$?

[redacted] (cont'd)

⑤ [[redacted]]. In Xerox class notes on "Propagation of Light: Dispersion" (3/9/89), we found a dispersion relation for a medium of absorbing atoms of resonant frequency ω_0 and spontaneous decay rate γ. For zero conductivity, Eq. (30) of the notes provides:

$$k^2 = \frac{\omega^2}{c^2}\left(\frac{\omega^2-\omega_1^2+i\gamma\omega}{\omega^2-\omega_0^2+i\gamma\omega}\right).$$

Here: $\omega_1^2 = \omega_0^2 + \omega_p^2$, where ω_p is the effective plasma freq. Normally $\omega_0 > \omega_p \gg \gamma$.

(A) Find the (complex) dielectric cnst $\epsilon(\omega)$ corresponding to the above dispersion relation. Separate $\epsilon(\omega)$ into its real & imaginary parts, $\mathrm{Re}\,\epsilon(\omega)$ & $\mathrm{Im}\,\epsilon(\omega)$.

(B) Sketch the behavior of $\mathrm{Re}\,\epsilon(\omega)$ & $\mathrm{Im}\,\epsilon(\omega)$ vs. ω. Be careful to show what happens near $\omega=\omega_0$. Comment on the physical effects shown by the medium near $\omega=\omega_0$.

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⑥ [[redacted]]. An EM pulse: $u(x,t)=\int_{-\infty}^{\infty} A(k)\, e^{i[kx-\omega(k)t]}\,dk$, propagates in a medium with a given dispersion relation $\omega=\omega(k)$. In general, $\omega(k)$ is a complex function of k. Anyway, as a measure of the energy transported by the pulse, we can construct and analyse the quantity: $\mathcal{E}(t)=\int_{-\infty}^{\infty}|u(x,t)|^2\,dx$.

(A) Comment on why $\mathcal{E}(t)$ is a reasonable measure of the pulse energy transport.

(B) Show that $\mathcal{E}(t)$ is independent of time [energy is conserved] unless $\mathrm{Im}\,\omega(k)\neq 0$.

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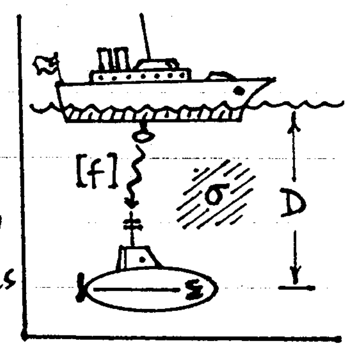
⑦ [[redacted]]. You are on a surface ship, trying to communicate with a submarine -- by means of broadcasting EM waves at frequency f through the water. The sub must remain submerged at depth D, and it cannot detect your signal if the signal power level falls below $\frac{1}{N}$ of its broadcast value ($N>1$). Assume that sea-water is a fairly good conductor, with conductivity σ.



(A) Show that ship → sub communication is possible only if: $D\sqrt{f} \lesssim$ some number, and express "some number" in terms of σ, N and appropriate constants.

(B) For actual numbers, assume $N=100$ (sub detects at 1% broadcast level), and take $\sigma(\text{sea-water}) = 4.3\,(\text{ohm-m})^{-1}$ [note MKS units]. If the sub remains at depth $D=100$ m, what is the maximum frequency f which can be used for messages?

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(1) [redacted]. Shine a feeble flashlight on a fat charge. What, me radiate?

(A) For "weak" fields, the problem is nonrelativistic, and q's acceleration a is given by:

$$ma = F = qE = qE_0 \sin\omega(t - \tfrac{z}{c}), \quad \mathbf{a} \text{ is along } \mathbf{E}_0, \tag{1}$$

i.e. Newton II. q will radiate (nonrelativistically) by Larmor's formula [Jk$^{\underline{n}}$ Eq. (14.22)]

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$$\left.\begin{array}{l}\text{energy/time}\\ \text{(all directions)}\end{array}\right\} \; P = \frac{2}{3}(q^2/c^3)\,|a|^2,$$

so/ $$P = \frac{2}{3}(q^4/m^2c^3)\,E_0^2 \sin^2\omega(t - \tfrac{z}{c}). \tag{2}$$

P of Eq. (2) is the instantaneous power. A time average $\Rightarrow \sin^2(\;) = \frac{1}{2}$, so

$$\boxed{P_{AV} = \frac{1}{3}(q^4/m^2c^3)\,E_0^2}, \tag{3}$$

is the desired average power radiated by q due to its motion in E.

(B) The above simple-minded treatment will fail when $\mathbf{E}$ is strong enough, or quickly-varying enough, so that q moves ~ relativistically. A rough criterion for when this happens can be quoted as follows.

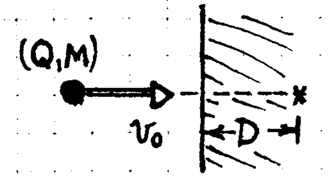
Since -- by Eq. (1) -- the acceleration: $a = (qE_0/m)\sin\omega(t - \frac{z}{c}) = \frac{dv}{dt}$, the velocity of the ensuing harmonic motion of q is: $v = -(qE_0/m\omega)\cos\omega(t - \frac{z}{c})$. v has maximum value: $v_M = (qE_0/m\omega)$, and if our nonrelativistic treatment is to be anywhere near good, we must impose...

$$v_M/c = qE_0/m\omega c \ll 1 \;\Rightarrow\; \boxed{E_0/\omega \ll mc/q} \leftarrow \text{nonrelativistic condition.} \tag{4}$$

This condition establishes what is meant by "weak fields". When the condition is violated, i.e. when: $\underline{E_0 \to (mc/q)\omega}$, the nonrelativistic approxn fails.

When $\omega \to 0$, we have a DC $\mathbf{E}$-field acting on q for a long time. It is then ~ impossible to avoid relativistic motion for q by the criterion of Eq. (4).

[redacted] Final Exam Solut[redacted] (cont'd)



⟨2⟩ [[redacted]]. Simple analysis of radiation from a stopping charge.

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(A) For cnst deceleration a, the (nonrel^{c}) Larmor radiation rate : $P = (2Q^2/3c^3)a^2$, is also cnst. And from simple kinematics, the stopping time is $t_s = v_0/a$. Total energy radiated during the event is ...

$$\mathcal{E} = Pt_s = (2Q^2/3c^3)a^2 \cdot \frac{v_0}{a}, \quad \text{or//} \quad \mathcal{E} = (2Q^2/3c^3)v_0 a. \tag{1}$$

To eliminate a, note that the stopping distance $D = v_0^2/2a$ (again from simple kinematics), so that $a = v_0^2/2D$. Then energy radiated is ...

$$\boxed{\mathcal{E} = \frac{Q^2}{3D}(v_0/c)^3}. \tag{2}$$

(B) The K.E. loss during the event is : $\Delta K = \frac{1}{2}Mv_0^2$, and the relative rad$^{\underline{n}}$ loss is given by the ratio

$$\mathcal{E}/\Delta K = \frac{2}{3}\left(\frac{1}{D}\frac{Q^2}{Mc^2}\right)\frac{v_0}{c}, \quad \text{i.e.//} \quad \boxed{\frac{\mathcal{E}}{\Delta K} = \frac{2}{3}\left(\frac{R}{D}\right)\frac{v_0}{c}}, \tag{3}$$

where : $R = Q^2/Mc^2$ = classical charge radius of Q.

Classical charge radii are <u>small</u>, e.g. for an electron $(-e, m)$, $R = e^2/mc^2 = 2.8 \times 10^{-13}$ cm [Jackson Eq. (14.104)]◆. So, if the penetration depth D in Eq. (3) is measured in Angstroms (10^{-8} cm), we have ...

$$\frac{\mathcal{E}}{\Delta K} \leqslant 2 \times 10^{-5}(\beta_0/D), \quad \beta_0 = v_0/c. \tag{4}$$

Now $D \sim 100$ at least (Q must collide with "many" atoms before stopping), and $\beta_0 \sim 0.1$ is reasonable. Then $\underline{\underline{\mathcal{E}/\Delta K < 2\times 10^{-8}}}$. As (almost) always, radiation loss is small compared to mechanical loss in a stopping event.

◆ $R \leqslant R$(electron) for any Q of a larger mass M than electron.

[redacted] Final Exam Soluti[redacted](cont'd)

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③ [redacted]. Analyse dispersion relation $\omega = \omega(k)$ such that $v_p v_g = \text{cnst} = v^2$.

(A) The $\omega = \omega(k)$ we are looking for obeys...

$$v_p v_g = \frac{\omega}{k}\frac{\partial \omega}{\partial k} = v^2,\ \text{cnst} \Rightarrow \frac{1}{2k}\frac{\partial}{\partial k}(\omega^2) = v^2$$

or// $\frac{\partial}{\partial k}(\omega^2) = 2kv^2$, so// $\omega^2 = k^2v^2 + \text{cnst}$ (1)

The most general dispersion relation is thus

$$\boxed{\omega(k) = v\sqrt{k^2 + k_0^2}},\ \text{where } k_0 = \text{cnst}. \quad (2)$$

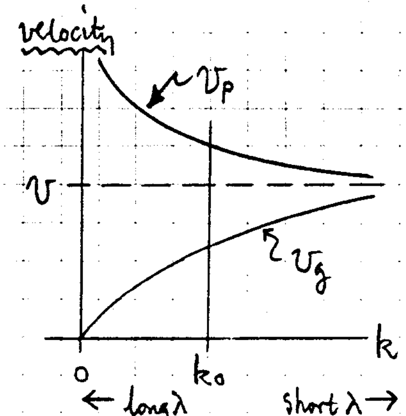
When $k_0 = 0$, this dispersion relation is that of light: $\omega = kc$ (w/ $v \to c$). When $k_0 \neq 0$, it describes a "plasma", or the high-frequency limit in a dielectric medium. See Jackson Eq. (7.61), p. 289.

(B) For the above $\omega = \omega(k)$, we form the velocities...

<u>phase</u>: $v_p = \dfrac{\omega}{k} = v\sqrt{1 + (k_0/k)^2} \longrightarrow \begin{cases} \infty, \text{ when } k \ll k_0; \\ v, \text{ when } k \gg k_0; \end{cases}$ (3)

<u>group</u>: $v_g = \dfrac{\partial \omega}{\partial k} = v^2/v_p = v/\sqrt{1 + (k_0/k)^2} \longrightarrow \begin{cases} 0, \text{ when } k \ll k_0, \\ v, \text{ when } k \gg k_0. \end{cases}$ (4)

Pictorially, v_p & v_g, as fcns of k, behave as in the sketch at right. Since the ratio...



$$v_p / v_g = 1 + (k_0/k)^2, \quad (5)$$

then $v_p = 2v_g$ when $k = k_0$.

The dispersion relation of Eq. (2) can be written as...

$\longrightarrow \omega = \sqrt{\omega_p^2 + (kv)^2}$, w/ $\omega_p = k_0 v = \text{cnst}$. (6)

For real $k^2 \geq 0$, must have $\boxed{\omega \geq \omega_p}$ for allowed propagation.

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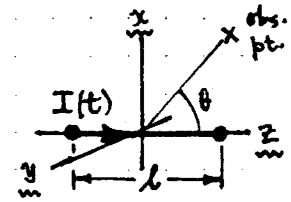
④ [redacted]. Freq. spectrum for turning on your toaster.



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1. From Eq. (18) of Xerox class notes of 1/27/89, and Prob. ㊹ on Asst. # 3, we know that the frequency spectrum which is broadcast by a current pulse $I(t)$ through a length l (in 1D) is given by

$$\rightarrow \sigma(\omega) = \left(\frac{\sin^2\theta}{4\pi c^3}\right)\frac{l^2}{2\pi}\left|\int_{-\infty}^{\infty}\dot{I}(t)e^{-i\omega t}dt\right|^2. \qquad (1)$$

$\sigma(\omega)$ is the energy radiated per unit freq. interval and per unit solid ∡ in the direction θ (θ is the colatitude ∡ w.r.t. the axis of the current -- see sketch above).

2. For our case, the current derivative, for $I(t) = I_0(1-e^{-t/\tau})$ @ $t \geqslant 0$, is

$$\dot{I}(t) = \begin{cases} 0, \text{ for } t<0 \text{ (since } I \equiv 0 \text{ @ } t<0); \\ (I_0/\tau)\,e^{-t/\tau}, \text{ at } t \geqslant 0. \end{cases} \qquad (2)$$

Then the Fourier integral in Eq. (1) is...

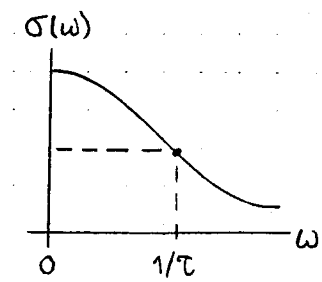
$$\int_{-\infty}^{\infty}\dot{I}(t)e^{-i\omega t}dt = (I_0/\tau)\int_0^{\infty}e^{-\left(\frac{1}{\tau}+i\omega\right)t}dt = I_0/(1+i\omega\tau), \qquad (3)$$

so// $\left|\int_{-\infty}^{\infty}\dot{I}(t)e^{-i\omega t}dt\right|^2 = I_0^2/[1+(\omega\tau)^2]$;

and// $$\boxed{\sigma(\omega) = \left(\frac{\sin^2\theta}{8\pi^2c^3}\right)I_0^2 l^2/[1+(\omega\tau)^2]}. \qquad (4)$$

Geometrically, the radiation is broadcast mainly in the plane which is perpendicular to (and which bisects) the current element.

3. The spectrum $\sigma(\omega)$ vs. ω in Eq. (4) describes a Lorentzian curve with maxm @ $\omega = 0$ and HWHM (half-width at half) at $\omega = 1/\tau$. As the turn-on time $\tau \to 0$, the spectrum becomes very broad, with much high-freq. present.



Thus, if you try to do anything too fast, you just create a lot of noise.

[redacted] cont'd)

(5) [[redacted]]. Find dielectric constant $\epsilon(\omega)$ for absorbing atom [$\sim$SHO] medium.

(A) By Jackson's Eq. (7.5), p. 270, ϵ is related to wave's (ω, k) by: $k = \omega/v = (\omega/c)\sqrt{\mu\epsilon}$. For the usual assumption that $\mu = 1$, we have -- using the given...

$$\rightarrow \epsilon(\omega) = \left(\frac{kc}{\omega}\right)^2 = \left[(\omega^2 - \omega_1^2) + i\gamma\omega\right] / \left[(\omega^2 - \omega_0^2) + i\gamma\omega\right] \quad \text{w/ conductivity } \alpha = 0, \; \text{\& } \omega_1^2 = \omega_0^2 + \omega_P^2. \quad (1)$$

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Make the denominator real by multiplying through by the complex conjugate...

$$\epsilon(\omega) = \frac{1}{\mathcal{D}(\omega)}\left[(\omega^2 - \omega_1^2) + i\gamma\omega\right]\left[(\omega^2 - \omega_0^2) - i\gamma\omega\right], \quad \text{w/} \left[\underline{\mathcal{D}(\omega)} = (\omega^2 - \omega_0^2)^2 + \gamma^2\omega^2;\right]$$

so/

$$\epsilon(\omega) = \mathrm{Re}\,\epsilon(\omega) + i\,\mathrm{Im}\,\epsilon(\omega) \begin{cases} \mathrm{Re}\,\epsilon(\omega) = \left[(\omega^2 - \omega_1^2)(\omega^2 - \omega_0^2) + \gamma^2\omega^2\right] / \mathcal{D}(\omega), \\ \mathrm{Im}\,\epsilon(\omega) = \gamma(\omega_1^2 - \omega_0^2)\,\omega / \mathcal{D}(\omega). \end{cases} \quad (2)$$

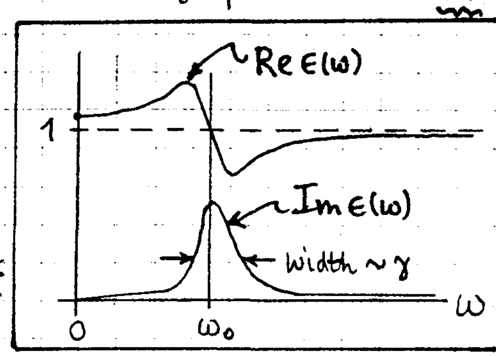
Put in $\omega_1^2 = \omega_0^2 + \omega_P^2$ and reorganize $\mathrm{Re}\,\epsilon(\omega)$ somewhat to get finally...

$$\boxed{\mathrm{Re}\,\epsilon(\omega) = 1 + \frac{\omega_P^2(\omega_0^2 - \omega^2)}{\mathcal{D}(\omega)}, \quad \mathrm{Im}\,\epsilon(\omega) = \gamma\omega_P^2\omega / \mathcal{D}(\omega).} \quad (3)$$

This is w/o approxn (except conductivity = 0). The denom. fcn $\mathcal{D}(\omega)$ is defined in (2).

(B) With $\omega_0 > \omega_P \gg \gamma$, we note the following ω-dependence of Eqs. (3)...

$$\begin{cases} \omega \to 0+ \Rightarrow \mathcal{D}(\omega) \to \omega_0^4, \text{ and: } \mathrm{Re}\,\epsilon(\omega) \to 1 + (\omega_P^2/\omega_0^2), \; \mathrm{Im}\,\epsilon(\omega) \to 0+; \\ \omega \to \omega_0- \Rightarrow \mathcal{D}(\omega) \to \gamma^2\omega_0^2 \text{ [MIN], and: } \mathrm{Re}\,\epsilon(\omega) \to 1+, \; \mathrm{Im}\,\epsilon(\omega) \to \frac{\omega_P^2}{\gamma\omega_0} \text{ [}\sim\text{MAX]}; \\ \omega \gg \omega_0 \Rightarrow \mathcal{D}(\omega) \sim \omega^4, \text{ and: } \mathrm{Re}\,\epsilon(\omega) \sim 1 - (\omega_P^2/\omega^2), \; \mathrm{Im}\,\epsilon(\omega) \sim \gamma\omega_P^2/\omega^3. \end{cases} \quad (4)$$



This behaviour, plus our general knowledge of the behavior of dielectric cnsts in absorbing media (see e.g. Jackson's Fig 7.8 on p. 286) permits the sketch at right. Evidently, there is a region of "anomalous dispersion" near ω_0 (the atomic absorption freq.), which is not surprising. Near ω_0, the medium's index of refraction $n(\omega) \simeq \sqrt{\mathrm{Re}\,\epsilon(\omega)}$ changes rapidly ($\Rightarrow$ strong refraction). Also, the attenuation parameter

$$\rightarrow \alpha(\omega) \sim \frac{\omega}{c}\left[\mathrm{Im}\,\epsilon(\omega)/n(\omega)\right] \leftarrow \text{from Jackson's Eq. (7.55)}, \quad (5)$$

is at a maxm as $\omega \sim \omega_0$. This means the medium absorbs strongly at $\omega \sim \omega_0$.

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(6) [redacted]. Contemplate energy transport for an EMP in a dispersive medium.

(A) Since $u(x,t)$ is a field amplitude, then $|u(x,t)|^2$ is proportional to an energy density in the pulse, and for a 1D problem, $|u(x,t)|^2 dx$ is proportional to the pulse energy (at time t) contained in the interval $x \to x+dx$. Then $\int_{-\infty}^{\infty} |u(x,t)|^2 dx = \mathcal{E}(t)$ is the total pulse energy at t (to within multiplicative cnsts).

(B) With $u(x,t) = \int_{-\infty}^{\infty} A(k)\, e^{i[kx - \omega(k)t]} dk$, k is real, but both $A(k)$ & $\omega(k)$ may be complex in general. Putting $u(x,t)$ into the integral for $\mathcal{E}$...

$$\rightarrow \mathcal{E}(t) = \int dx\, |u(x,t)|^2 \quad \text{... all integrals are } \int_{-\infty}^{\infty} \text{ ... } \omega = \omega(k) \text{...} \qquad (1)$$

$$= \int dx \left(\int dk\, A(k)\, e^{i(kx - \omega t)} \right)^* \left(\int dk' A(k')\, e^{i(k'x - \omega' t)} \right)$$

$$= \int dk\, A^*(k)\, e^{+i\omega^* t} \int dk' A(k')\, e^{-i\omega' t} \underbrace{\int dx\, e^{-i(k-k')x}}_{= 2\pi\delta(k-k') \,[\text{delta fcn}]}. \qquad (2)$$

So...

$$\mathcal{E}(t) = 2\pi \int dk\, A^*(k)\, e^{i\omega^*(k)t} \int dk' A(k')\, e^{-i\omega(k')t}\, \delta(k-k'),$$

↑ k' integration gives $A(k)\, e^{-i\omega(k)t}$;

i.e.//
$$\mathcal{E}(t) = 2\pi \int_{-\infty}^{\infty} dk\, |A(k)|^2\, e^{-i[\omega(k) - \omega^*(k)]t}. \qquad (3)$$

But $\omega - \omega^* = 2i\, \mathrm{Im}\,\omega$, so finally -- and without approximation...

$$\boxed{\mathcal{E}(t) = 2\pi \int_{-\infty}^{\infty} dk\, |A(k)|^2\, e^{[2\,\mathrm{Im}\,\omega(k)]t}}. \qquad (4)$$

Evidently, if $\mathrm{Im}\,\omega(k) \equiv 0$, i.e. $\omega(k)$ = pure real, then $\mathcal{E}(t)$ is t-indpt; we just get: $\mathcal{E}(t) = 2\pi \int_{-\infty}^{\infty} |A(k)|^2 dk = \mathcal{E}(0)$, and the pulse energy is conserved (although the pulse can disperse). When $\omega(k)$ has an imaginary part $\mathrm{Im}\,\omega(k) < 0$ (somewhere), the pulse energy $\mathcal{E}(t)$ decreases.

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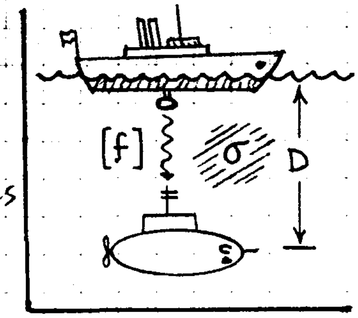
⑦ [[redacted]]. Show why submarines are mostly incommunicado.



(A) The broadcast signal field amplitudes fall off with depth as $e^{-(x/\delta)}$, where δ is the "skin depth" [Jackson Eq. (7.77)]...

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$$\rightarrow \delta = c/\sqrt{2\pi\mu\sigma\omega} \quad \begin{cases}\text{set } \mu=1 \\ \& \ \omega = 2\pi f\end{cases} \Rightarrow \delta = (c/2\pi\sqrt{\sigma})\frac{1}{\sqrt{f}}. \tag{1}$$

The signal power level (intensity) goes as $(e^{-x/\delta})^2$, and if we want the signal level to remain at or above $1/N$ of its broadcast value at $x=D$...

$$(e^{-D/\delta})^2 \geq \frac{1}{N} \Rightarrow e^{2D/\delta} \leq N, \text{ or } 2D \leq \delta \ln\sqrt{N} \tag{2}$$

Putting in δ from Eq. (1), we find the limiting situation for messages...

$$\boxed{D\sqrt{f} \leq (c/2\pi\sqrt{\sigma})\ln\sqrt{N}}. \tag{3}$$

(B) For numbers, take $\sigma(\text{seawater}) = 4.3(\text{ohm-m})^{-1}$, in MKS, and note that

$$\sigma_{CGS} = 9\times10^9\,\sigma_{MKS} = 3.87\times10^{10}\,\text{Hz} \leftarrow \text{from Jackson TABLE 4, p. 820} \tag{4}$$

With $c = 3\times10^{10}$ cm/sec, the numerical coefficient in Eq. (3) is: $(c/2\pi\sqrt{\sigma}) = 2.43\times10^4\ \text{cm}/(\text{Hz})^{1/2}$. Converting the depth D to meters, we have

$$\rightarrow D\sqrt{f} \leq 243 \ln\sqrt{N}, \quad D \text{ in m } \& \ f \text{ in Hz}. \tag{5}$$

If $N = 100$ (i.e. sub can detect broadcast signal down to 1% of its initial value, then $\ln\sqrt{N} = \ln 10 = 2.3026$, and Eq. (5) reads...

$$\rightarrow D\sqrt{f} \leq 506, \quad D \text{ in meters } \& \ f \text{ in Hz } (@\ 1/N = 1\%). \tag{6}$$

Finally if $D = 100$ m, then $\underline{\underline{f = (5.06)^2 = 25.6 \text{ Hz}}}$ is the maximum signal frequency which can be used to communicate with the sub.