EVALUATION OF GROUND MOTION & VIBRATION ON LINEAR COLLIDERS

GROUND MOTION IN FUTURE ACCELERATORS

ICFA WORKSHOP

NOV. 8, 2000

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- THIS WORK WAS (LARGELY) COMPLETED IN 1995 —

- COMBINED EFFORTS OF

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- IS WRITTEN UP IN ZDR - SLAC REP. 474

VOL. 2. APPENDIX C p 1043

CHAP 11 GROUND MOTION (IN FINAL FOCUS) p 718.

$P(\omega)$ $\mu m^2/Hz$ $\langle \Delta y^2 \rangle_t = \int P(\omega) \frac{d\omega}{2\pi}$.

$P(\omega) > 0$

ay
al $P(\omega, k_z)$ $P(\omega) = \int P(\omega, k) \frac{dk}{2\pi}$

$P(\omega,k) > 0$

$$\mu(\omega, k) \equiv \frac{P(\omega,k)}{P(\omega)} \qquad \int \mu(\omega,k) \frac{dk}{2\pi} = 1$$

$\mu(\omega,k) > 0$

→ μ a probability measure

→ $P(\omega)$ varies dramatically -

$\mu(\omega,k)$ "appears" to be ≈ constant -

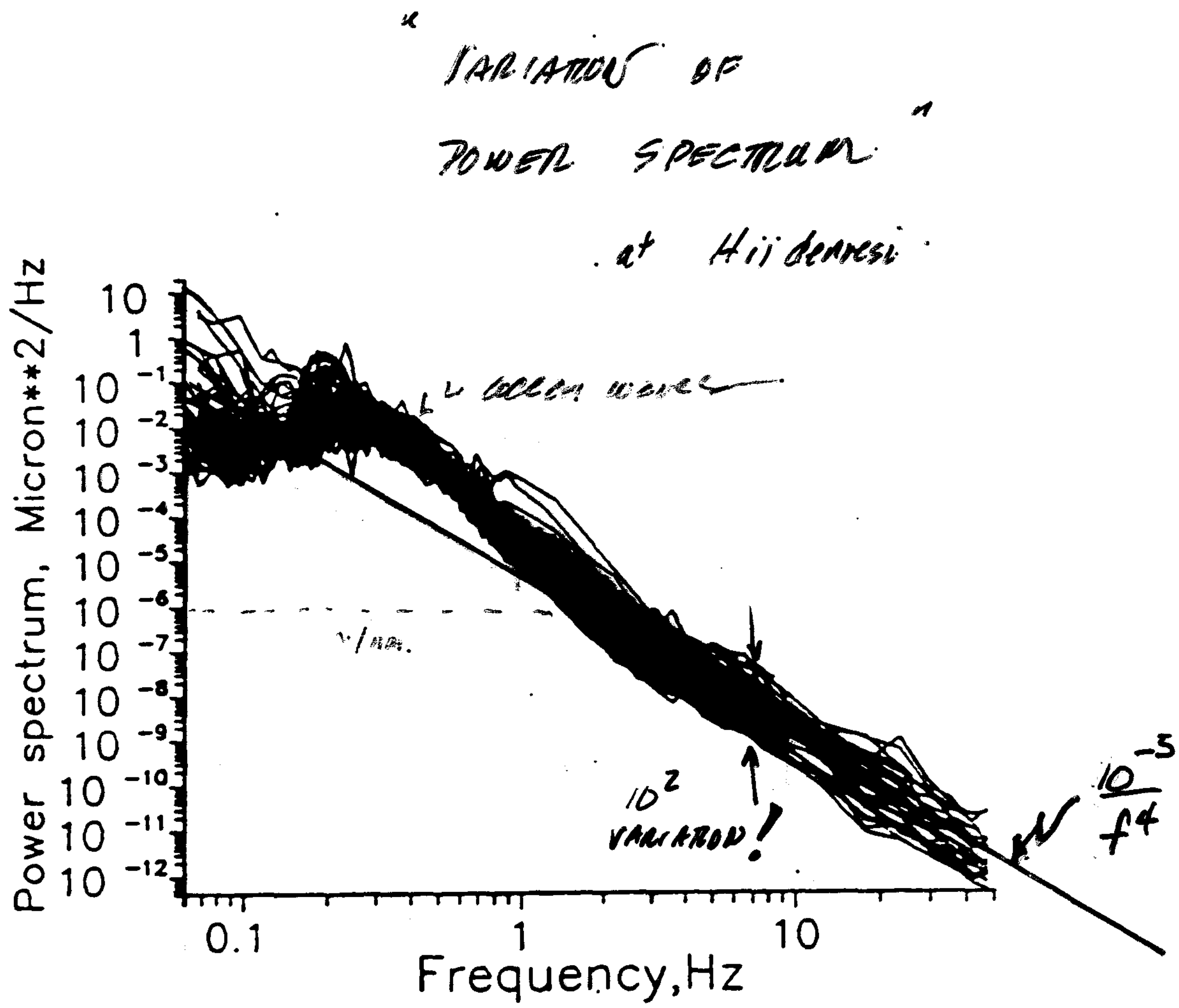


Fig.7. Variation of the power spectrum measured in Hiidenvesi in August 12-19, 1994.

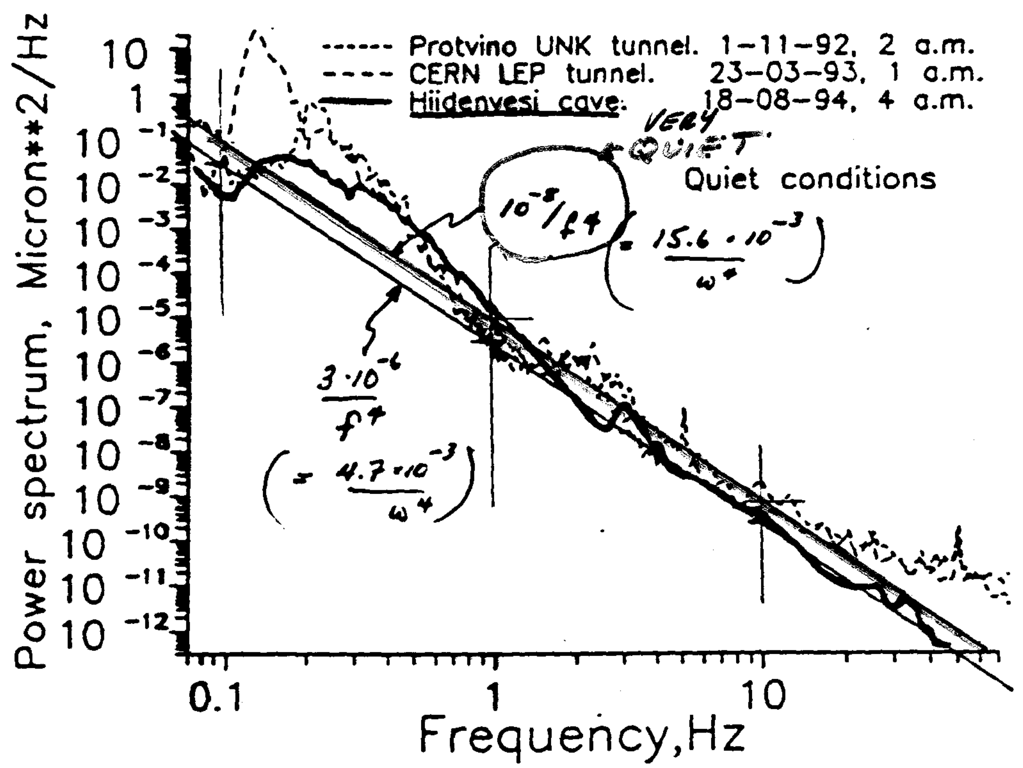
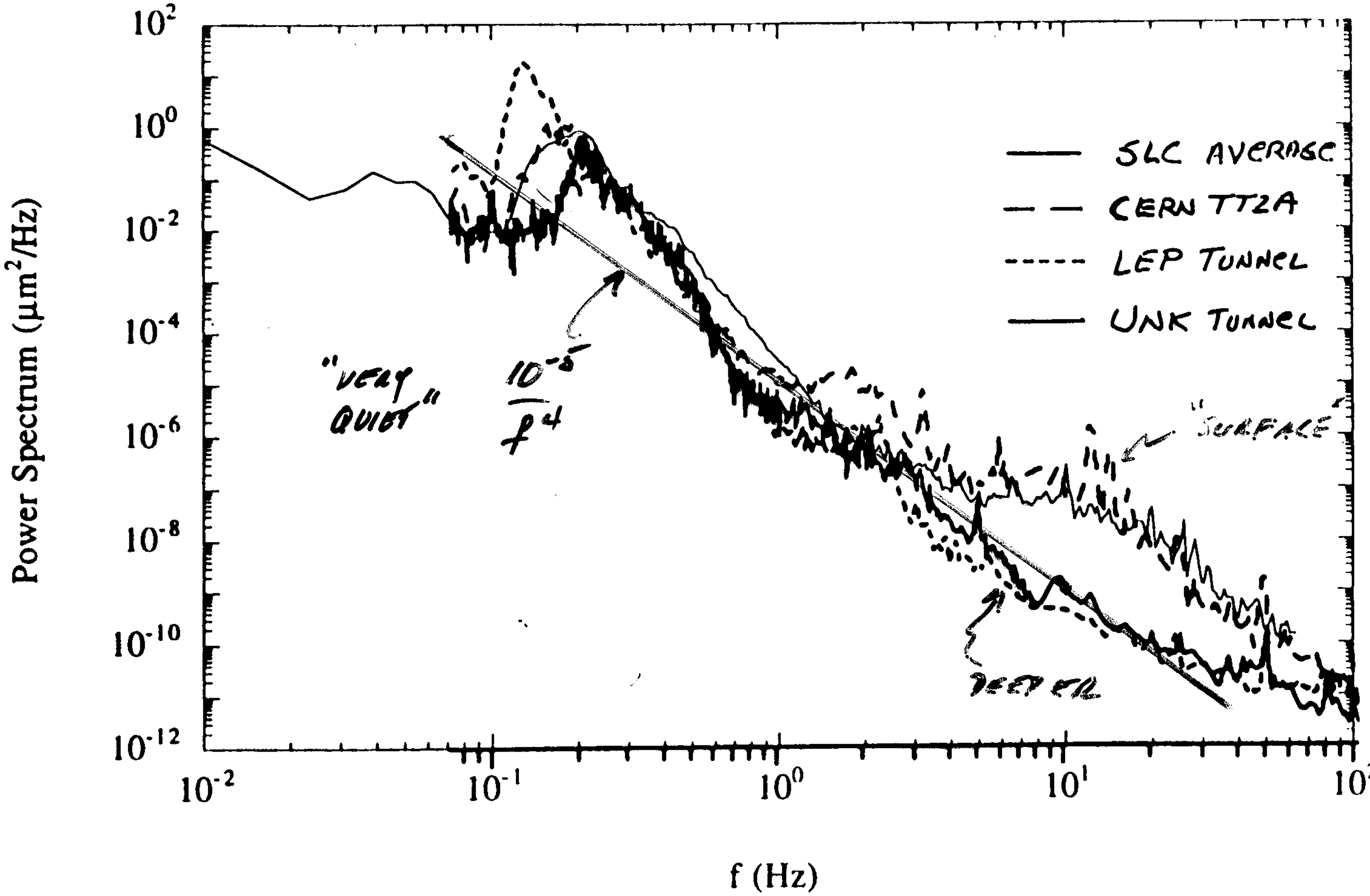
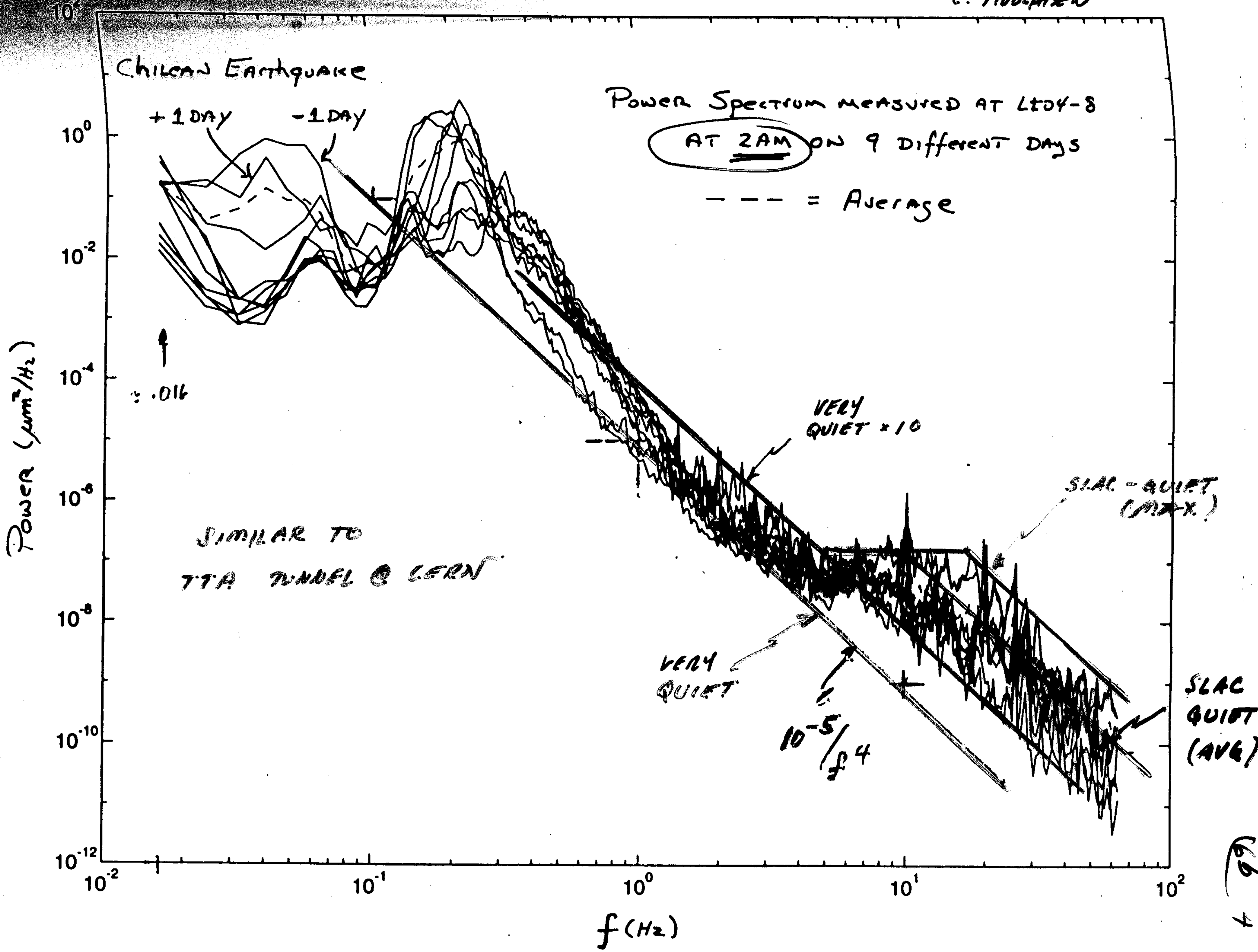


Fig.2. Power spectra of vertical seismic vibrations measured in Russia (Protvino, UNK tunnel), in Switzerland (CERN LEP tunnel) [4] and in Finland (Hiidenvesi cave) in quiet conditions.


Power Spectrum (μm²/Hz)
f (Hz)
SLC AVERAGE
CERN TT2A
LEP TUNNEL
UNK TUNNEL
"VERY QUIET"
10⁻⁵ / f⁴
"SURFACE"
DEEP CIL

C. ADOLPHSEN


Chilean Earthquake
+1 DAY
-1 DAY
POWER SPECTRUM MEASURED AT LI04-8
AT 2AM ON 9 DIFFERENT DAYS
- - - = Average
.016
VERY QUIET ×10
SLAC - QUIET (MAX)
SIMILAR TO
TTA TUNNEL @ CERN
VERY QUIET
$10^{-5}/f^4$
SLAC QUIET (AVG)
Power (μm^2/Hz)
f (Hz)
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-2}
10^{-1}
10^0
10^1
10^2

2.A.4 THE RATIO $R(\omega, \ell)$

$$< [y(t, s+\ell) - y(t,s)]^2 >_s$$

$$= 2 \left[\int P(\omega) \frac{d\omega}{2\pi} - \int\int P(\omega,k) \cos k\ell \frac{dk}{2\pi} \frac{d\omega}{2\pi} \right]$$

$$= 2 \int\int_0^\infty P(\omega, k) [1 - \cos k\ell] \frac{dk}{2\pi} \frac{d\omega}{2\pi}$$

$$= 2 \int_0^\infty P(\omega) \frac{d\omega}{2\pi} \underbrace{\int_0^\infty \mu(\omega, k) [1 - \cos k\ell] \frac{dk}{2\pi}}_{\equiv R(\omega, \ell)}$$

$$= 2 \int_0^\infty P(\omega) R(\omega, \ell) \frac{d\omega}{2\pi}$$

So SPECTRAL DENSITY OF $[y(t, s+\ell) - y(t,s)]^2$

is spectral density of $y(t,s)$

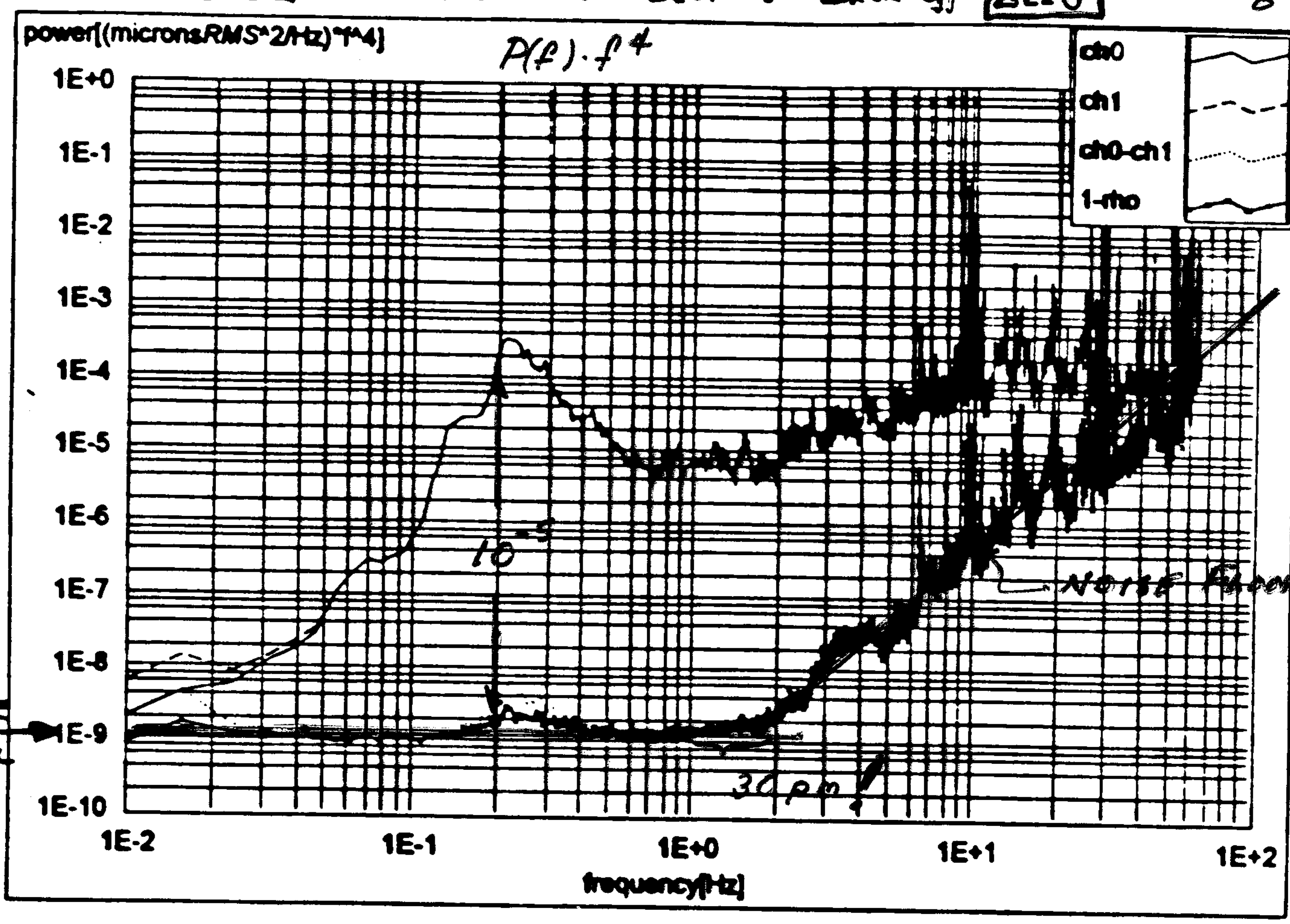
multiplied by

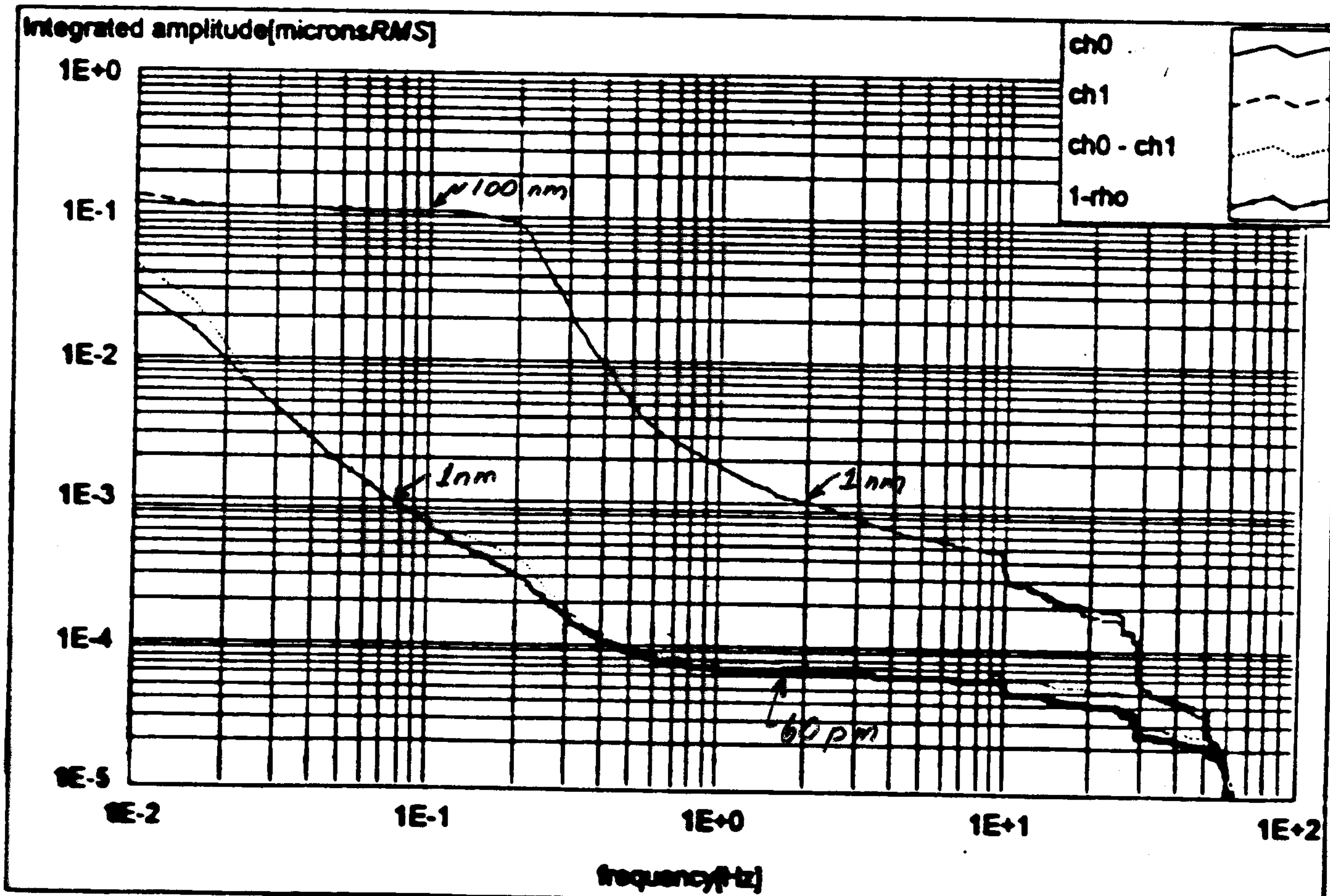
$$2 R(\omega, \ell)$$

CAN GET THIS DIRECTLY FROM DATA.

MEASURE $R \rightarrow$ EXTRACT μ

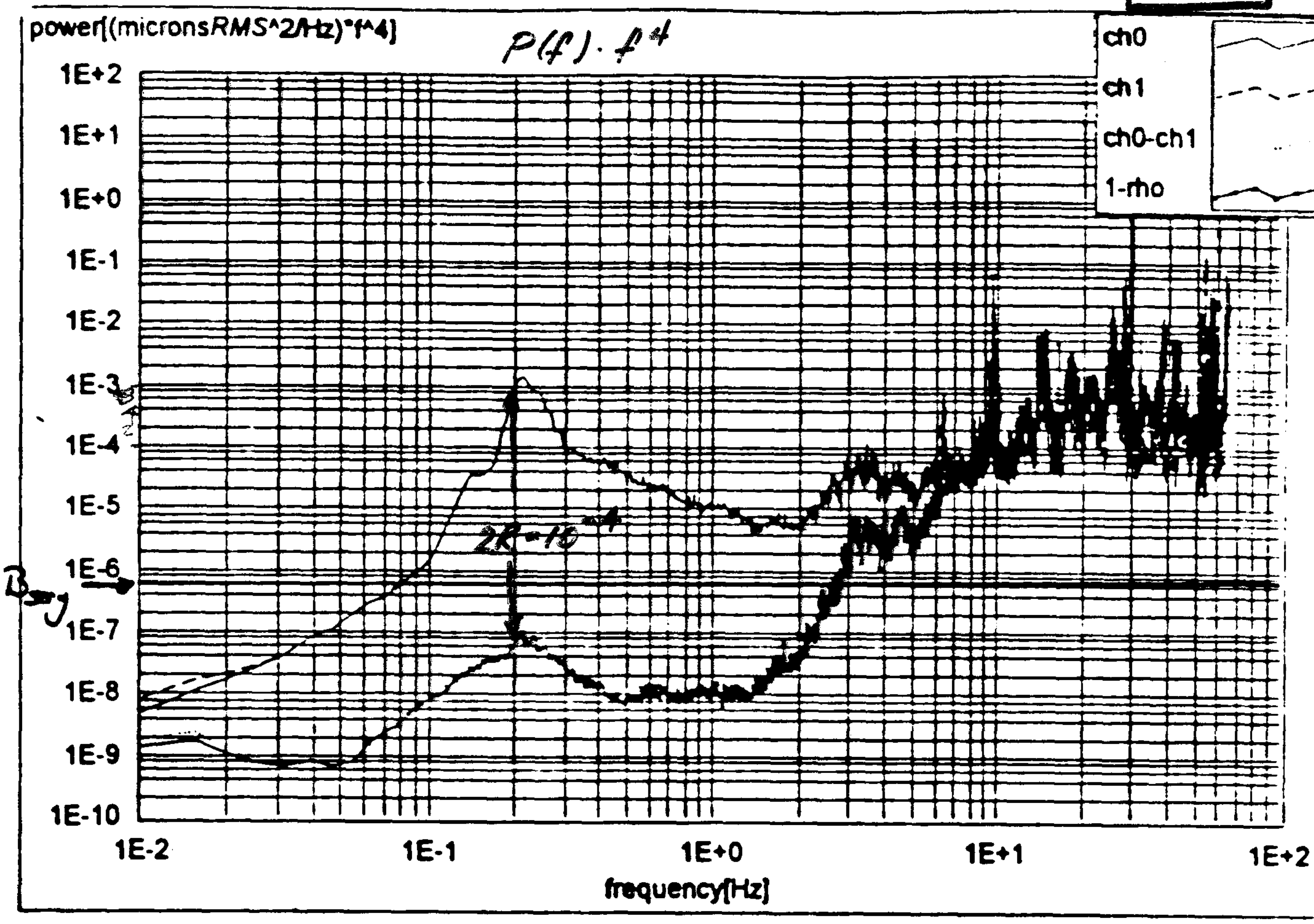
STS 2 MEASUREMENTS IN LIOF-8 WATER OFF ΔZ=0   8   12C

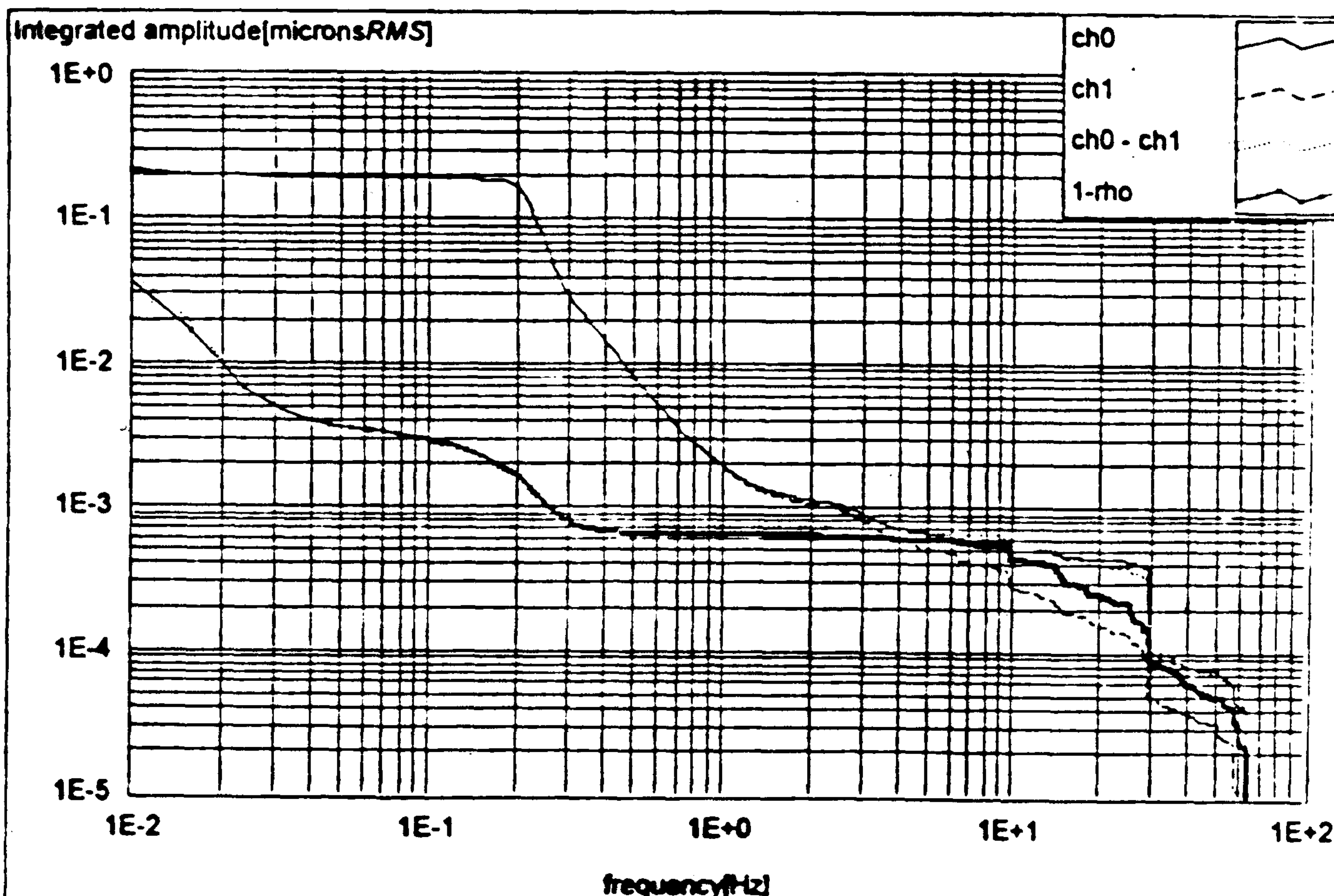




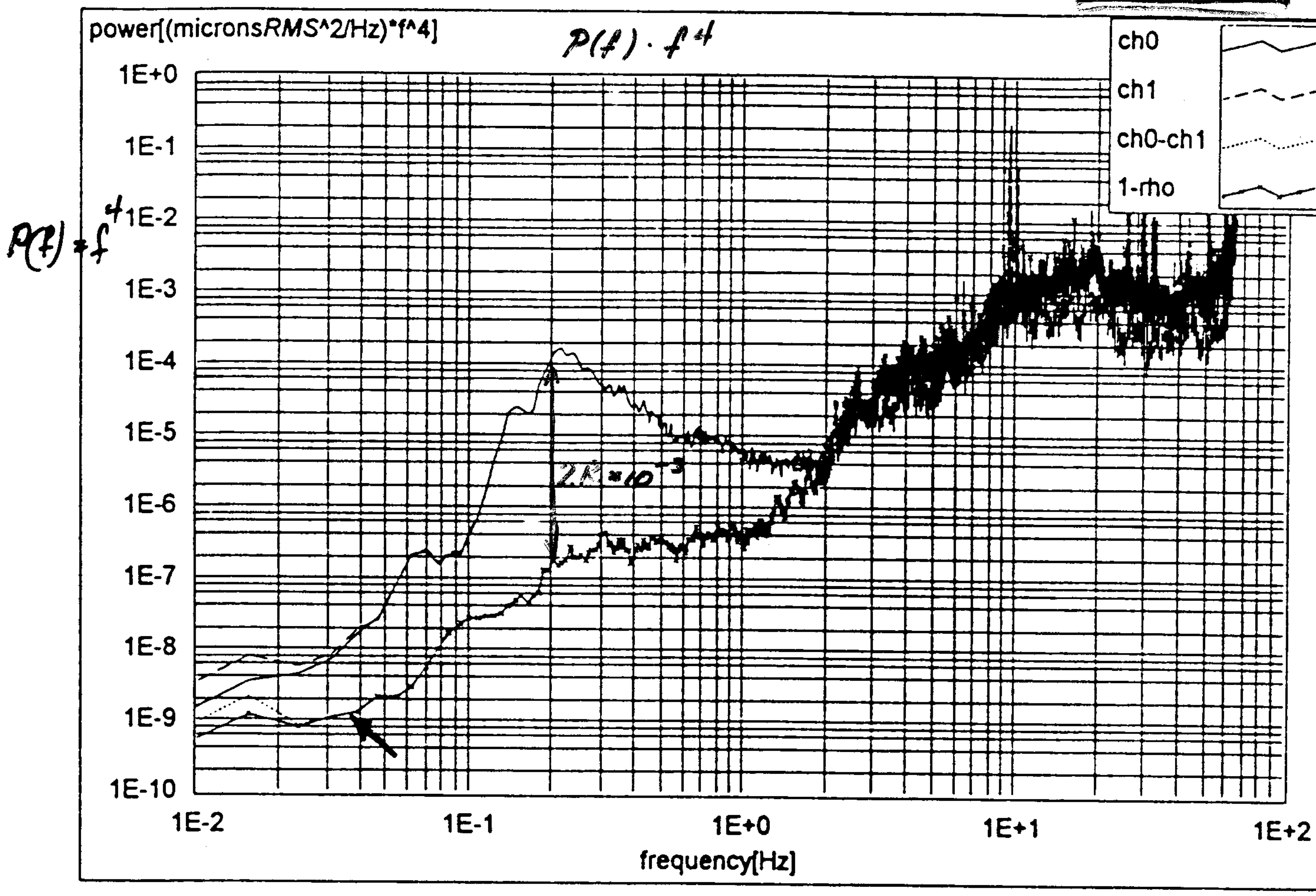
4 Δz=12m

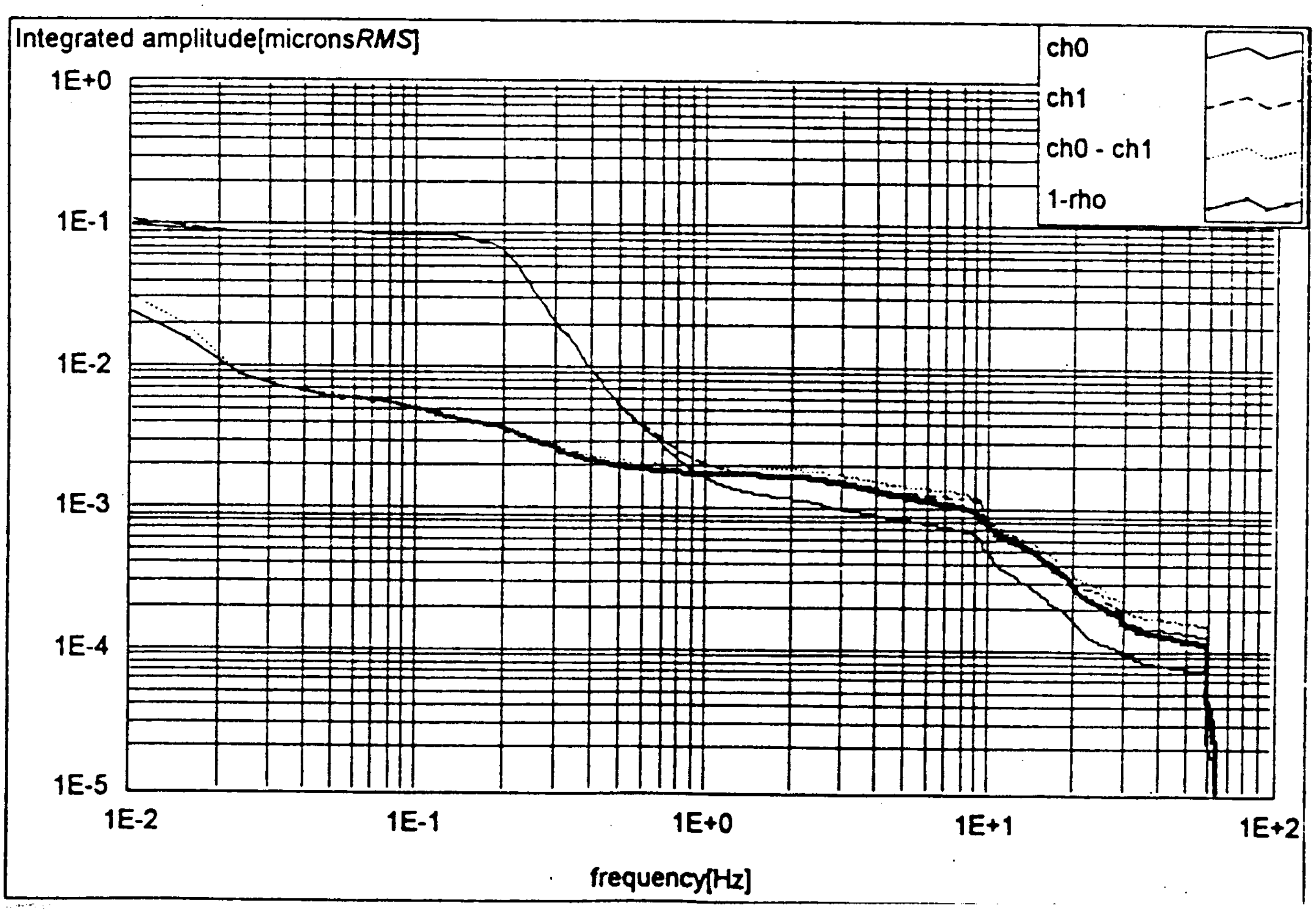
15c


power[(micronsRMS^2/Hz)*f^4]
P(f)·f^4
ch0
ch1
ch0-ch1
1-rho
1E+2
1E+1
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
2R=10^-4
Bsys
1E-2
1E-1
1E+0
1E+1
1E+2
frequency[Hz]


Integrated amplitude[micronsRMS]
ch0
ch1
ch0 - ch1
1-rho
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-2
1E-1
1E+0
1E+1
1E+2
frequency[Hz]

10 ΔZ = 100 m (13

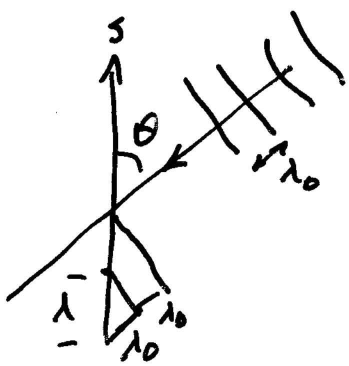

power[(micronsRMS^2/Hz)*f^4]
P(f) · f^4
P(f) * f^4
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-2
1E-1
1E+0
1E+1
1E+2
frequency[Hz]
ch0
ch1
ch0-ch1
1-rho


Integrated amplitude[micronsRMS]
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-2
1E-1
1E+0
1E+1
1E+2
frequency[Hz]
ch0
ch1
ch0 - ch1
1-rho

SUPPOSE "WAVES" OF FREQUENCY ω

had a fixed wavenumber $k_0(\omega)$ $\left[= \frac{\omega}{c(\omega)}\right]$

SUPPOSE THEY WERE ARRIVING FROM ALL DIRECTIONS.



$$\frac{d\theta}{(\pi/2)} = \text{fraction at angle } d\theta \quad \Big\langle \text{ UNIFORM in } \theta. \text{ "0 to } \pi/2\text{"}$$

$$= \frac{2}{\pi}\, dk\, \frac{d\theta}{dk}$$

$\lambda_0 = \lambda \cos\theta$

$k = k_0 \cos\theta$

$\left|\frac{dk}{d\theta}\right| = + k_0 \sin\theta$

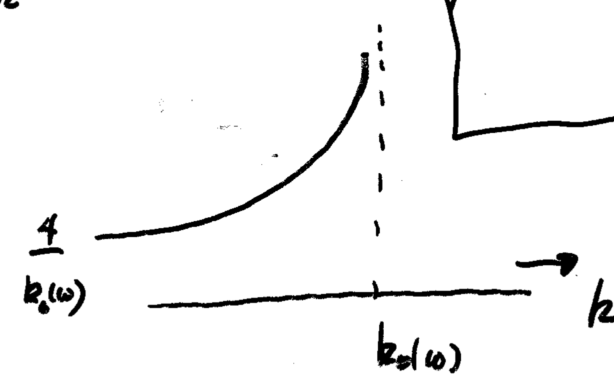
$$= k_0\sqrt{1-\cos^2\theta}$$

$$= \sqrt{k_0^2 - k^2}$$

$$= \frac{2}{\pi}\, dk\, \frac{1}{k_0 \sin\theta}$$

$$= \frac{2}{\pi}\, \frac{dk}{\sqrt{k_0^2(\omega) - k^2}} \quad \text{fraction in interval } dk.$$

$$\boxed{\mu(\omega, k) = \frac{4}{\sqrt{k_0^2(\omega) - k^2}}}$$



SUPPOSE WE HAVE WAVES - AT ω.

$$\mu(\omega, k) = \frac{4}{\sqrt{k_0(\omega)^2 - k^2}}$$

$$R(\omega,l) = \int \mu(\omega, k) \left[1 - \cos kl \right] \frac{dk}{2\pi}$$

$$= 1 - J_0 \left[k_0(\omega) \cdot l \right]$$

also $\Rightarrow \frac{k_0^2 l^2}{4}$ as $l \to 0$

VERY SPECIAL PREDICTION

SUPPOSE ONLY

$$\overline{k^2}(\omega) \equiv \int k^2 \mu(\omega, k) \frac{dk}{2\pi} < \infty$$

then as $l \to 0$

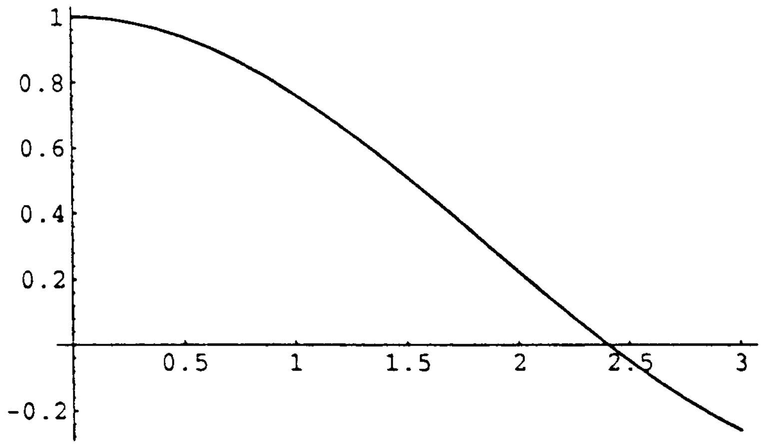
$$R(\omega, l) = \int_0^\infty \mu(\omega, k) \underbrace{\left[1 - \cos kl\right]}_{\approx \frac{1}{2} k^2 l^2} \frac{dk}{2\pi} \to \frac{1}{2} \overline{k^2}(\omega) \cdot l^2$$

ALSO QUITE SPEC for $k_{rms} l \ll 1$

[$l \to 0$ mean $l \ll \lambda$ content of μ! $kl \ll 1$ typ. k of μ!]

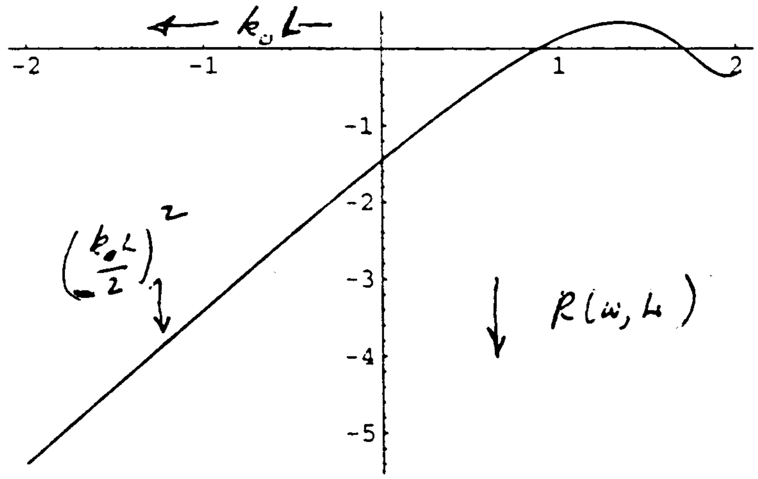
"Uniform wave assumption"

Plot[BesselJ[0,s],{s,0,3}]



-Graphics-

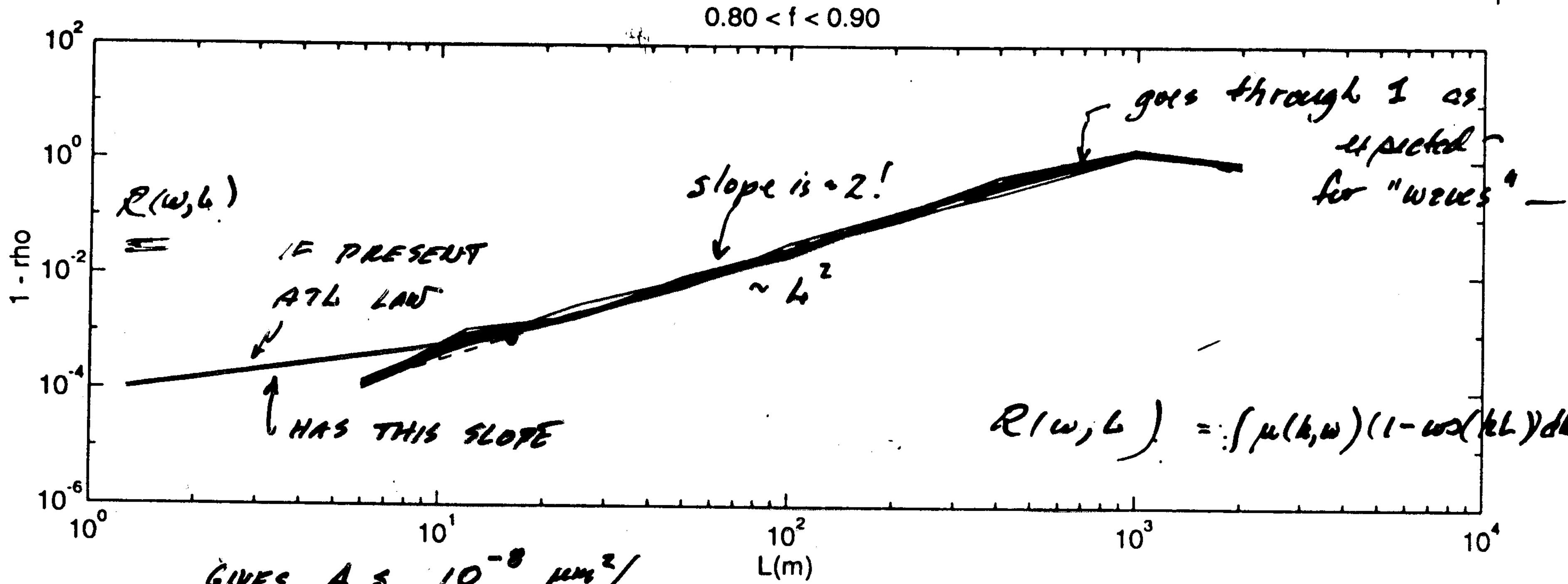
Plot[Log[1-BesselJ[0,Exp[t]]],{t,-2,2}]



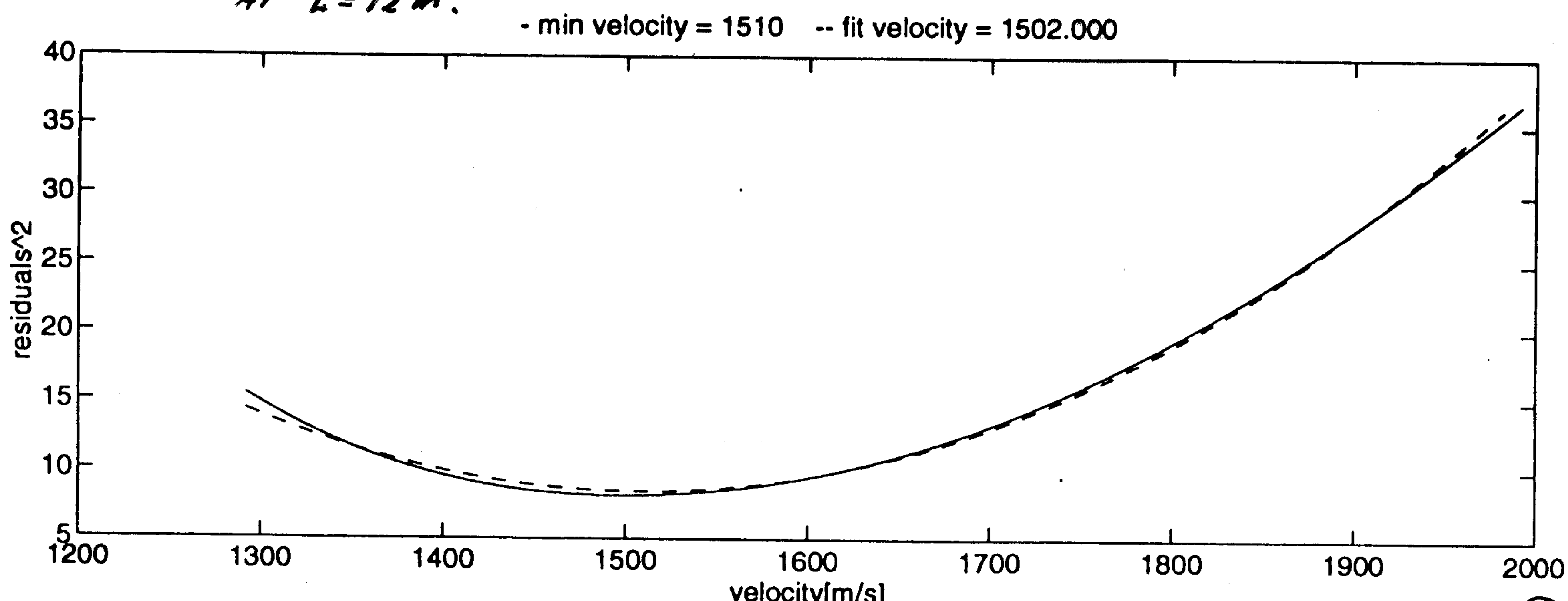
-Graphics-

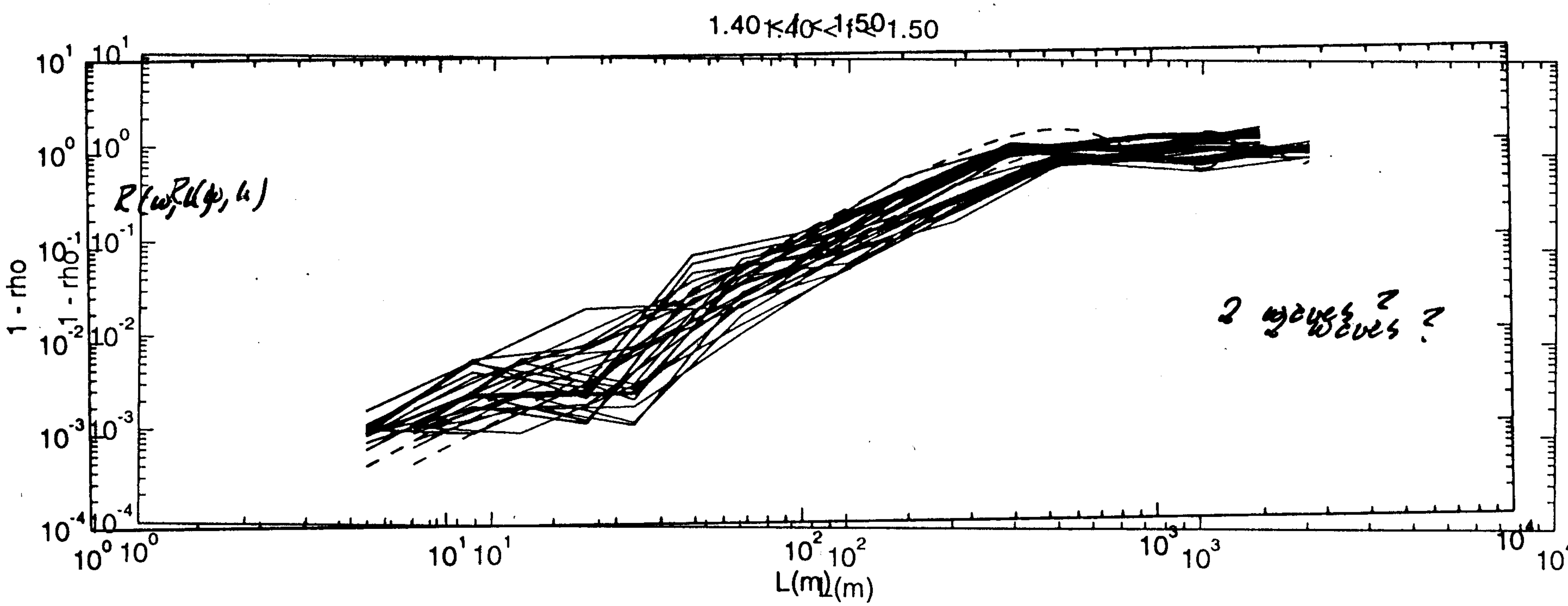
"k_0 can depend on frequency –"

$$J_0(k_0L) = \int_0^{k_0} \frac{dk}{2\pi} \underbrace{\left(\frac{2}{\pi}\right) \frac{4}{\sqrt{k_0^2 - k^2}}}_{\mu(k,\omega)} \cdot \cos kL$$

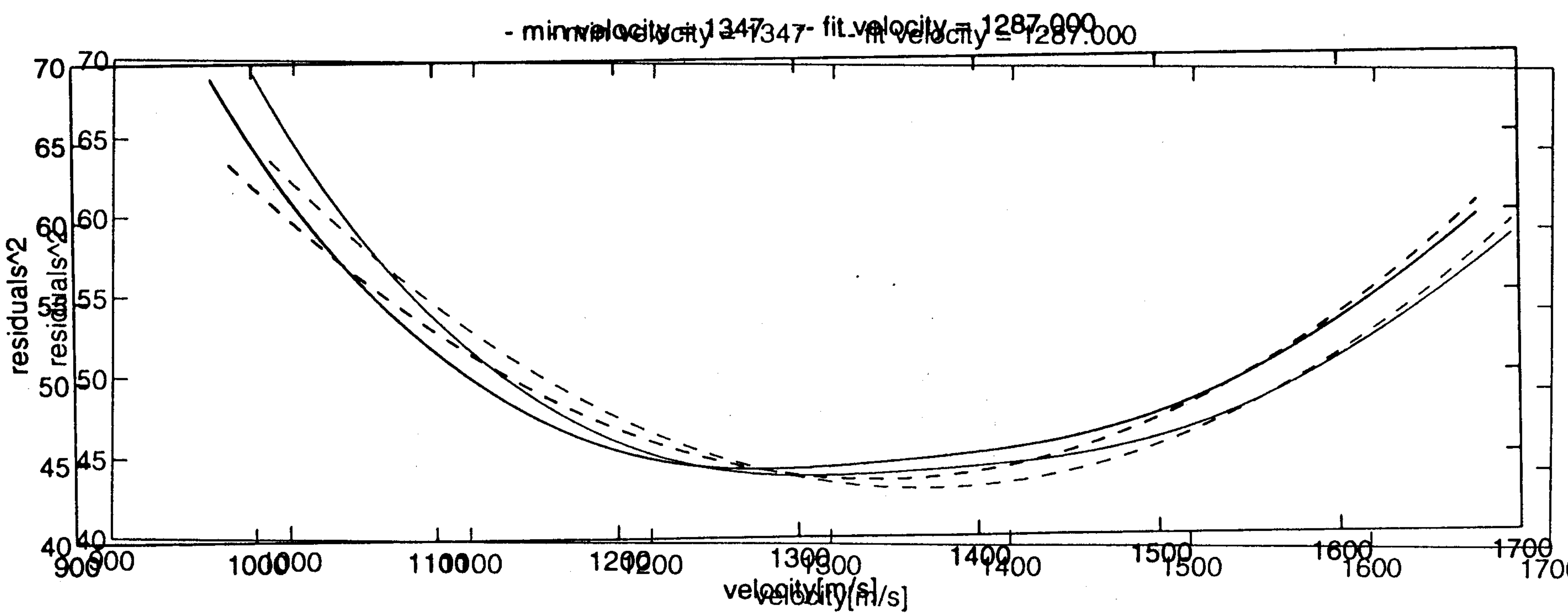


GIVES A ≤ 10^{-8} $\mu m^2/m\cdot s$
AT L = 12 m.



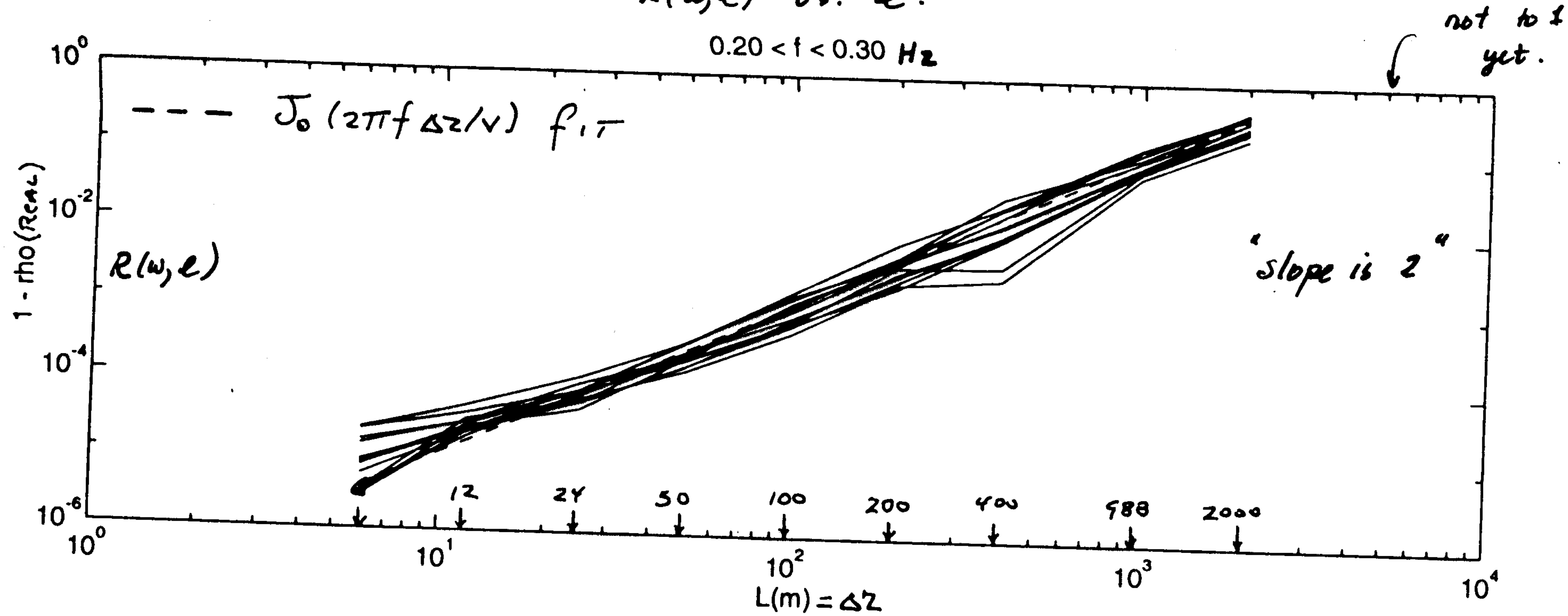


1.40 < f < 1.50
1 - rho
L(m)
2 waves ?

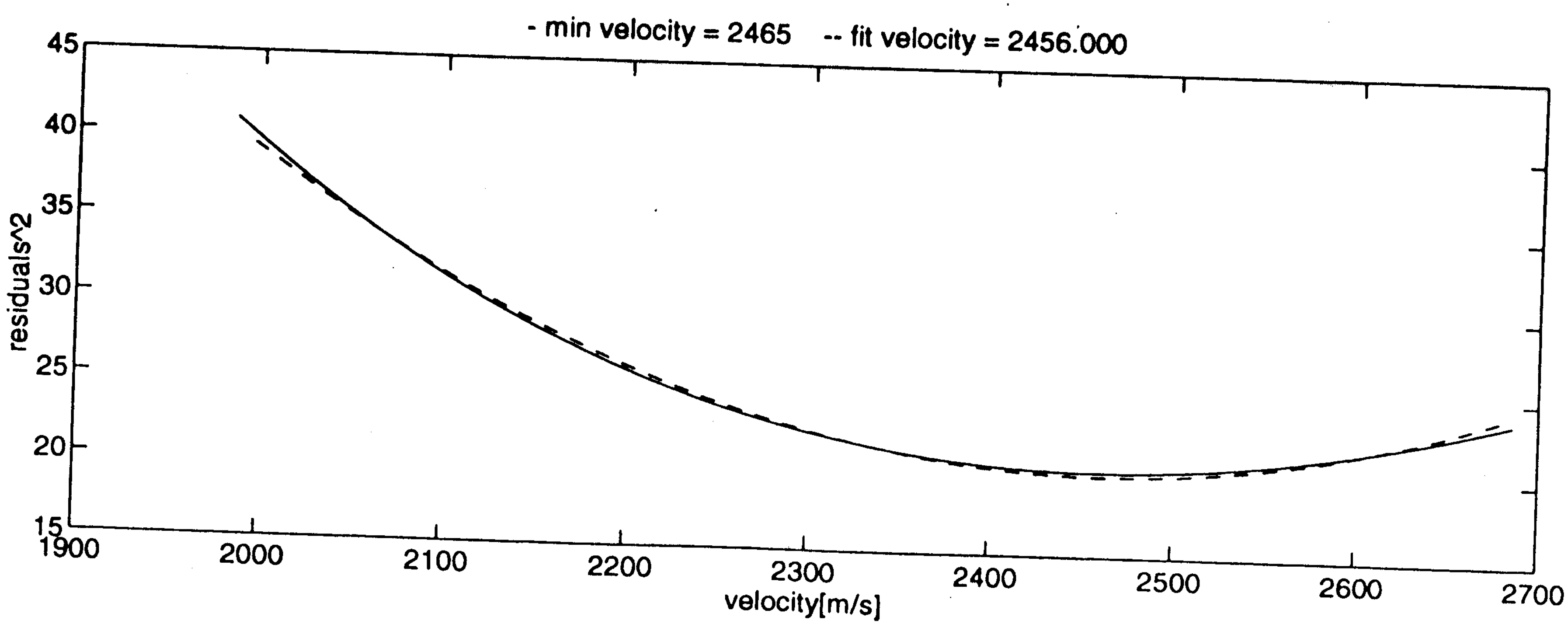


- min velocity = 1347 - fit velocity = 1287.000
residuals^2
velocity[m/s]

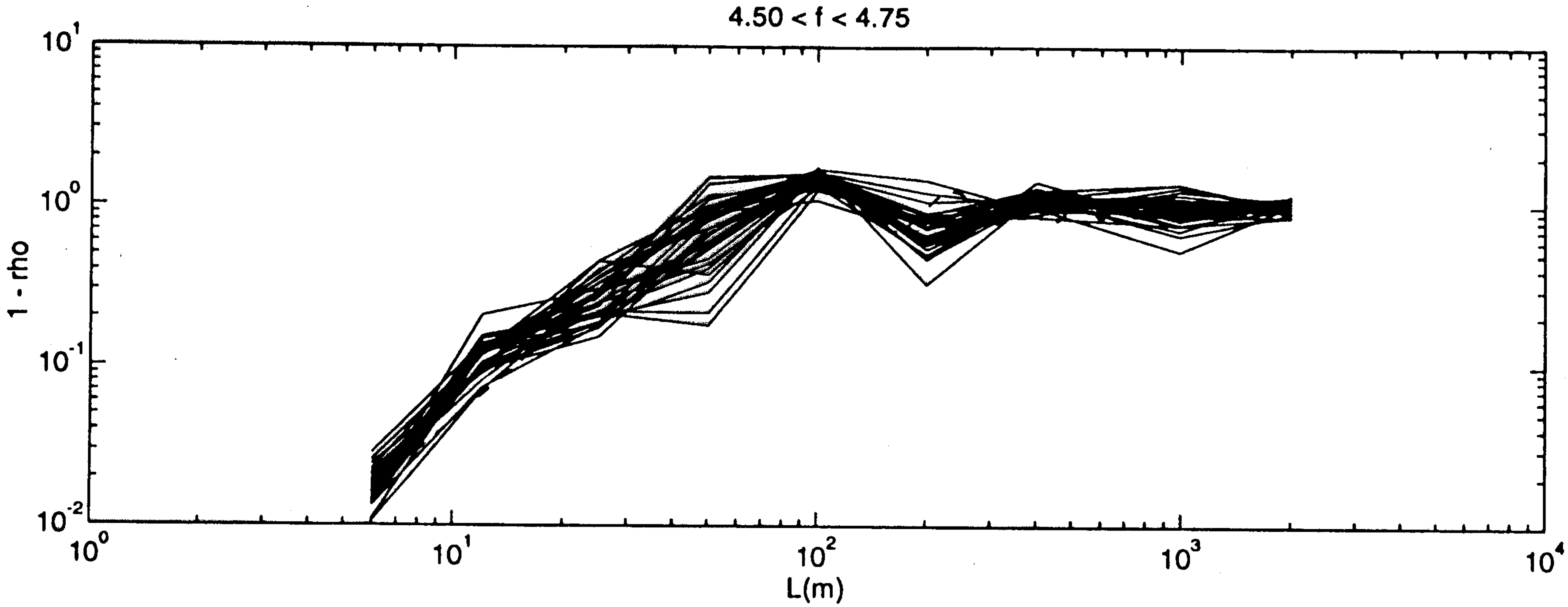
R(ω,ℓ) vs. ℓ.



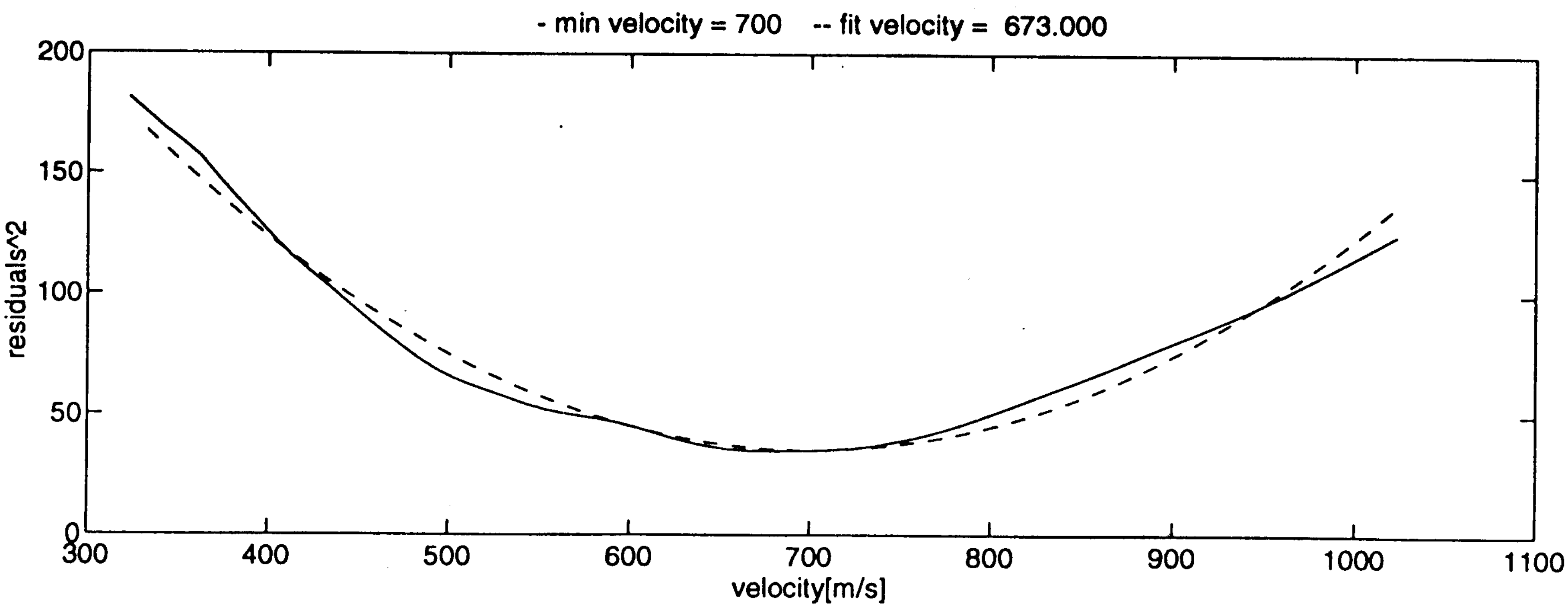
not to 1 yet.
0.20 < f < 0.30 Hz
--- $J_0(2\pi f \Delta z/v)$ fit
1 - rho(Real)
R(ω,ℓ)
"slope is 2"
12
24
50
100
200
400
988
2000
L(m) = Δz



- min velocity = 2465 -- fit velocity = 2456.000
residuals^2
velocity[m/s]



4.50 < f < 4.75
1 - rho
10^1
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
10^3
10^4
L(m)



- min velocity = 700 -- fit velocity = 673.000
residuals^2
200
150
100
50
0
300
400
500
600
700
800
900
1000
1100
velocity[m/s]

REMARKS ON ATL LAW.

ATL Law implies

$$\mu(\omega, k) = \mu_R(\omega, k) + \mu_T(\omega, k)$$

with $\quad \mu_T(\omega, k) \to \dfrac{A}{k^2\omega^2} \quad$ as $k \to \infty$

For $\mu_T(\omega, k) \qquad \int k^2 \mu_T(k, \omega)\, dk \to \infty.$

so ℓ^2 behavior not implied —

$$R(\omega, \ell) \sim \int \frac{1}{k^2} (1 - \cos k\ell) \frac{dk}{2\pi}$$

$$= 2\int \frac{\sin^2 \frac{k\ell}{2}}{k^2} \frac{dk}{2\pi} = \frac{\ell}{2\pi} \underbrace{\int \frac{\sin^2 x}{x^2}\, dx}_{\text{exists}}$$

exists —

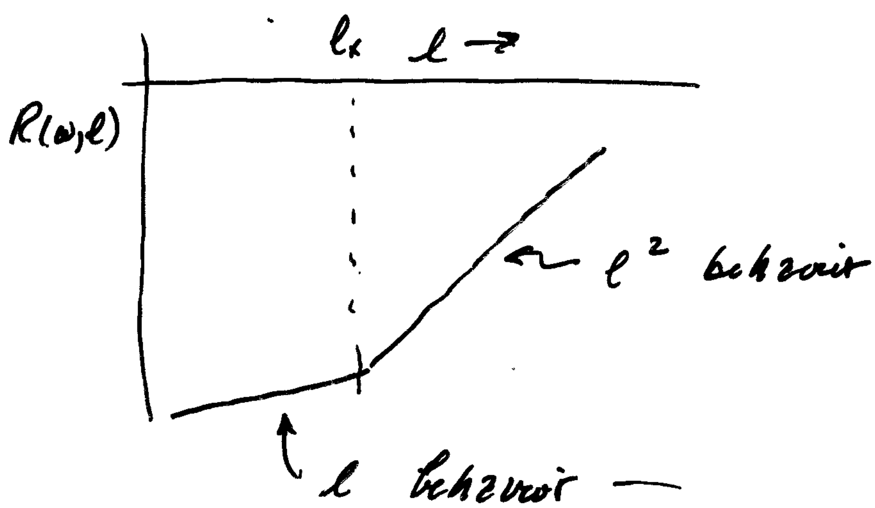
↑ get ℓ behavior!

IF A T L Law is present —

$$R(\omega, \ell) \to \alpha \ell^2 + \beta \ell \qquad \text{as } \ell \to 0$$

↑

at $\ell_x = \frac{\beta}{\alpha}$ 2 terms are equal.



From $R(\omega,\ell)$ data can put a limit on β!

$\Rightarrow$ $A < 0.6 \times 10^{-6}$ $\quad 0.1 < f < 10$

[SERY & NAPOLY ASSUME $A = 10^{-4}$ to 10^{-5}.]

LATTICE MOTION

$$G(k) \equiv \frac{\langle \Delta y_{IP}^2 \chi(k) \rangle}{y_0(k)^2}$$

plane wave response
— avg. over phase —

$$G(k) \sim k^6 \text{ as } k \to 0$$

FOR "PAIRED" LATTICES

$$G_\mu(\omega) \equiv \int G(k)\, \mu(\omega,k)\, \frac{dk}{2\pi}$$

$F(\omega) \equiv$ POWER SUPRESSION FROM FEEDBACK SYSTEM

$$\langle \Delta y_{IP}^2 \rangle = \int P(\omega,k)\, G(k)\, F(\omega)\, \frac{dk}{2\pi}\frac{d\omega}{2\pi}$$

$$= \int P(\omega)\, G_\mu(\omega)\, F(\omega)\, \frac{d\omega}{2\pi}$$

— THE LATTICE RESPONSE FUNCTION —

$$\Delta y_B(t) \equiv y_B(t) - y(t,0)$$

$$= \int_0^L K(s)\, y(t,s)\, R_{34}(s)\, ds + R_{33}(L)\, y(t,L) - y(t,0)$$

$$= \sum_i \mu_i\, y(t, s_i) \qquad \text{(slices)}$$

$$\langle \Delta y_B(t)^2 \rangle_t = \sum_{i,j} \mu_i \mu_j \langle y(t,s_i)\, y(t,s_j) \rangle_t$$

$$= \sum_{i,j} \mu_i \mu_j \int_0^\infty P(k) \cos[k(s_i - s_j)] \frac{dk}{2\pi}$$

$$= \int_0^\infty P(k) \underbrace{\sum_{i,j} \mu_i \mu_j \cos[k(s_i - s_j)]} \frac{dk}{2\pi}$$

$$G(k) \equiv \sum_i \mu_i \mu_j (\cos ks_i \cos ks_j + \sin ks_i \sin ks_j)$$

$$\boxed{G(k) = \left(\sum_i \mu_i \cos ks_i\right)^2 + \left(\sum_i \mu_i \sin ks_i\right)^2}$$

$$= \int_0^\infty P(k)\, G(k) \frac{dk}{2\pi}$$

Δy^2 response to sin wave, $\lambda = \frac{2\pi}{k}$.

FOR TWO FINAL FOCUS SYSTEMS.

$$\sum \mu_i \cos k s_i = 0 \qquad \text{by symmetry}$$

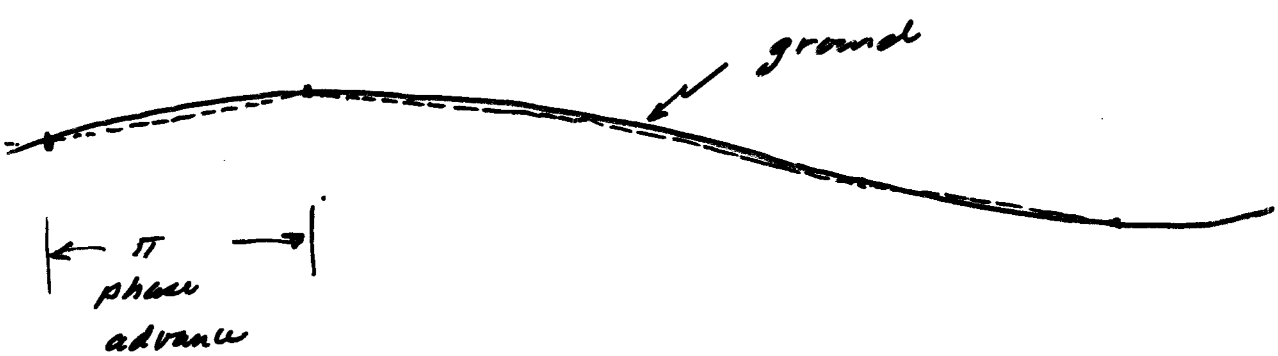
HENCE

$$\boxed{G(k) = 4\Big(\sum_{\substack{i \\ \text{one} \\ \text{side}}} \mu_i \sin k s_i\Big)^2}$$

"SUM RULES"

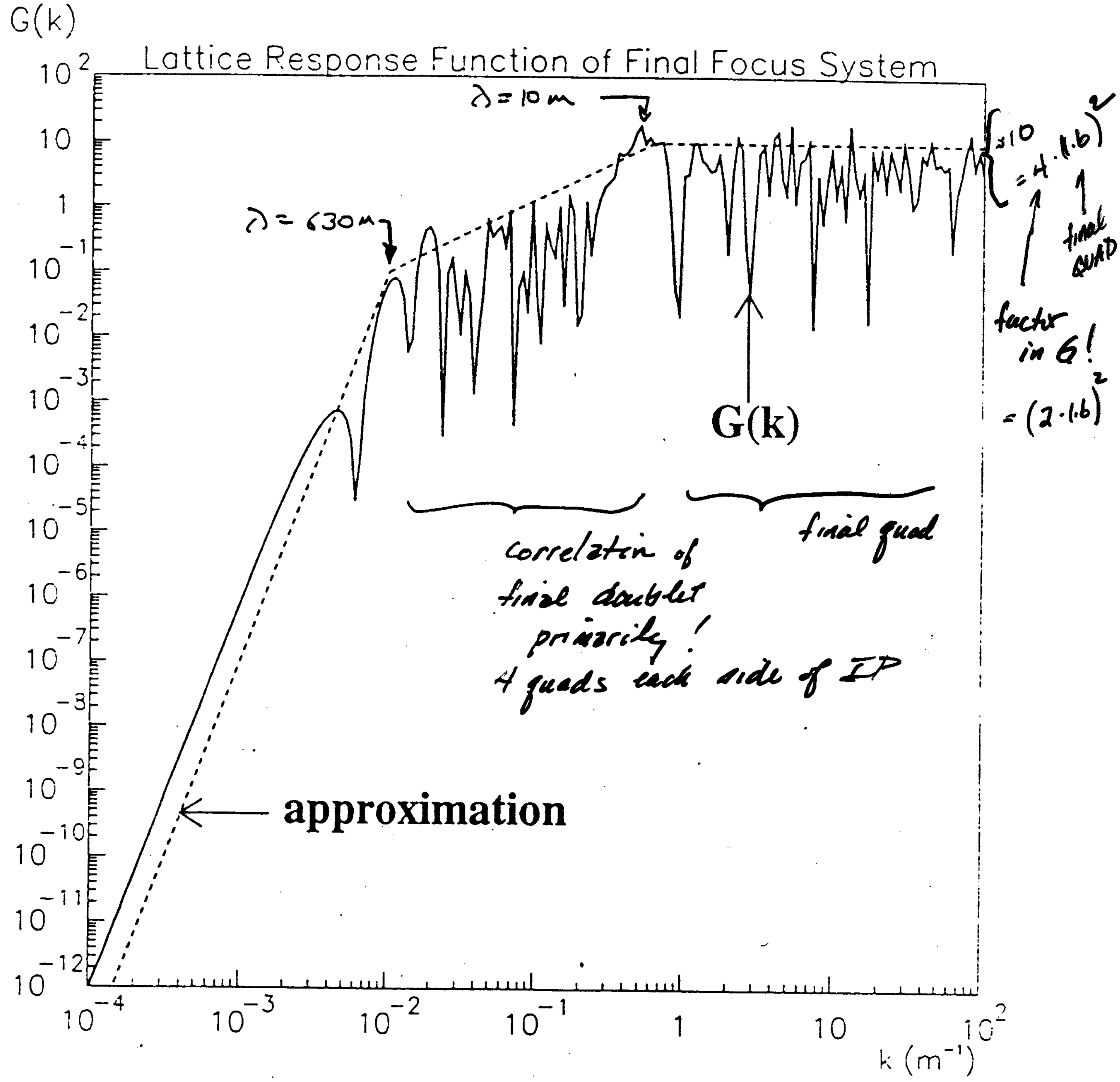
note: $\sum \mu_i s_i = 0$ so $G(k) \sim k^4$ $k \to 0$

but in a paired lattice $G(k) \sim k^6$!



for straight line approx —

$\Delta y_B = 0$!



$\frac{\lambda}{4} = \frac{630}{4} \approx 160$ m is length of π sections in FF system.

Zimmermann

TO GET A SPECTRAL DECOMPOSITION OF $\langle \Delta y_B(t)^2 \rangle$?

$$\langle \Delta y_B(t)^2 \rangle_t = \int_0^\infty P(\omega, k)\, G(k)\, \frac{dk}{2\pi}\, \frac{d\omega}{d\omega}$$

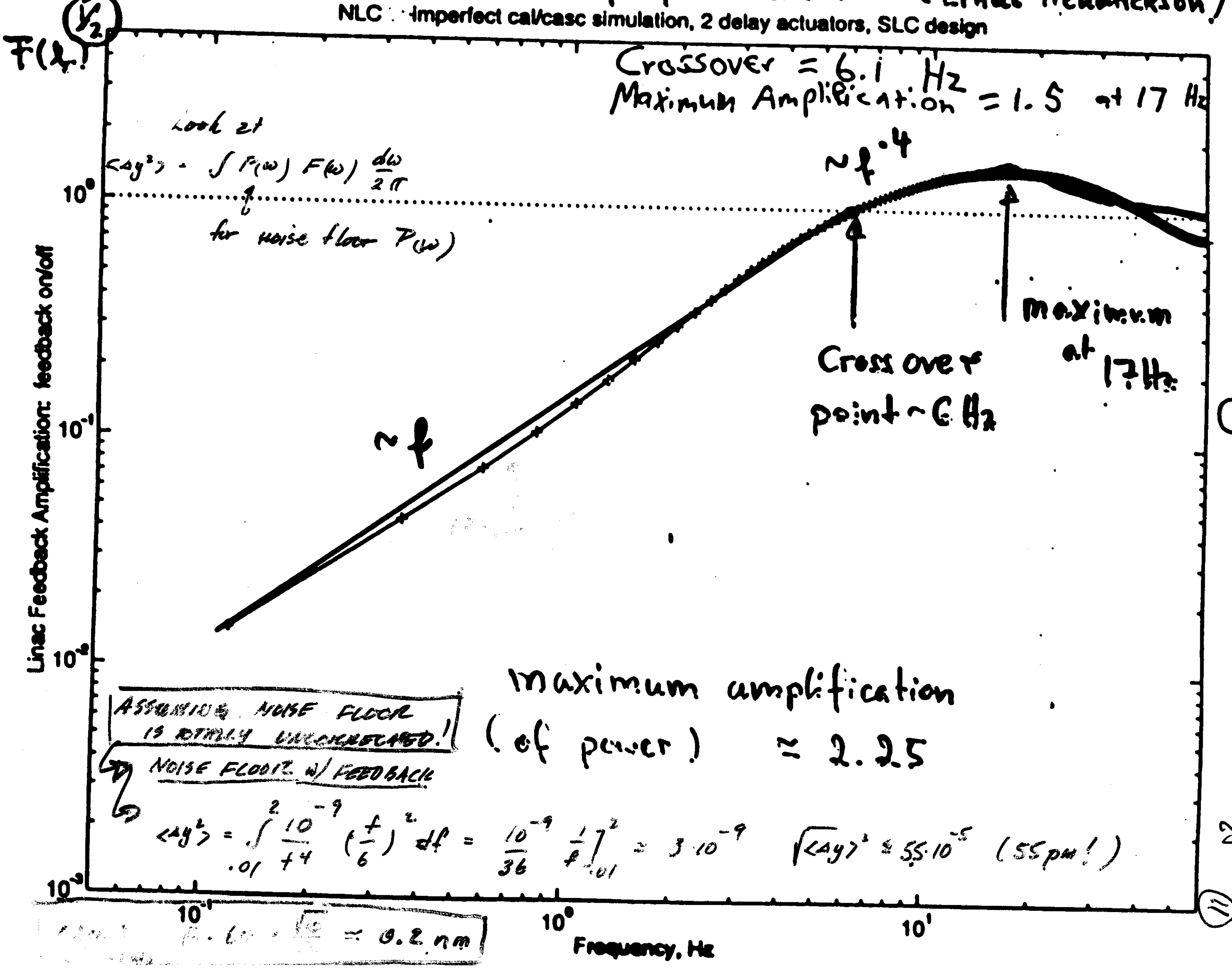
$$= \int_0^\infty P(\omega) \underbrace{\int_0^\infty \mu(\omega, k)\, G(k)\, \frac{dk}{2\pi}}_{\equiv\, G_\mu(\omega)} \cdot \frac{d\omega}{2\pi}$$

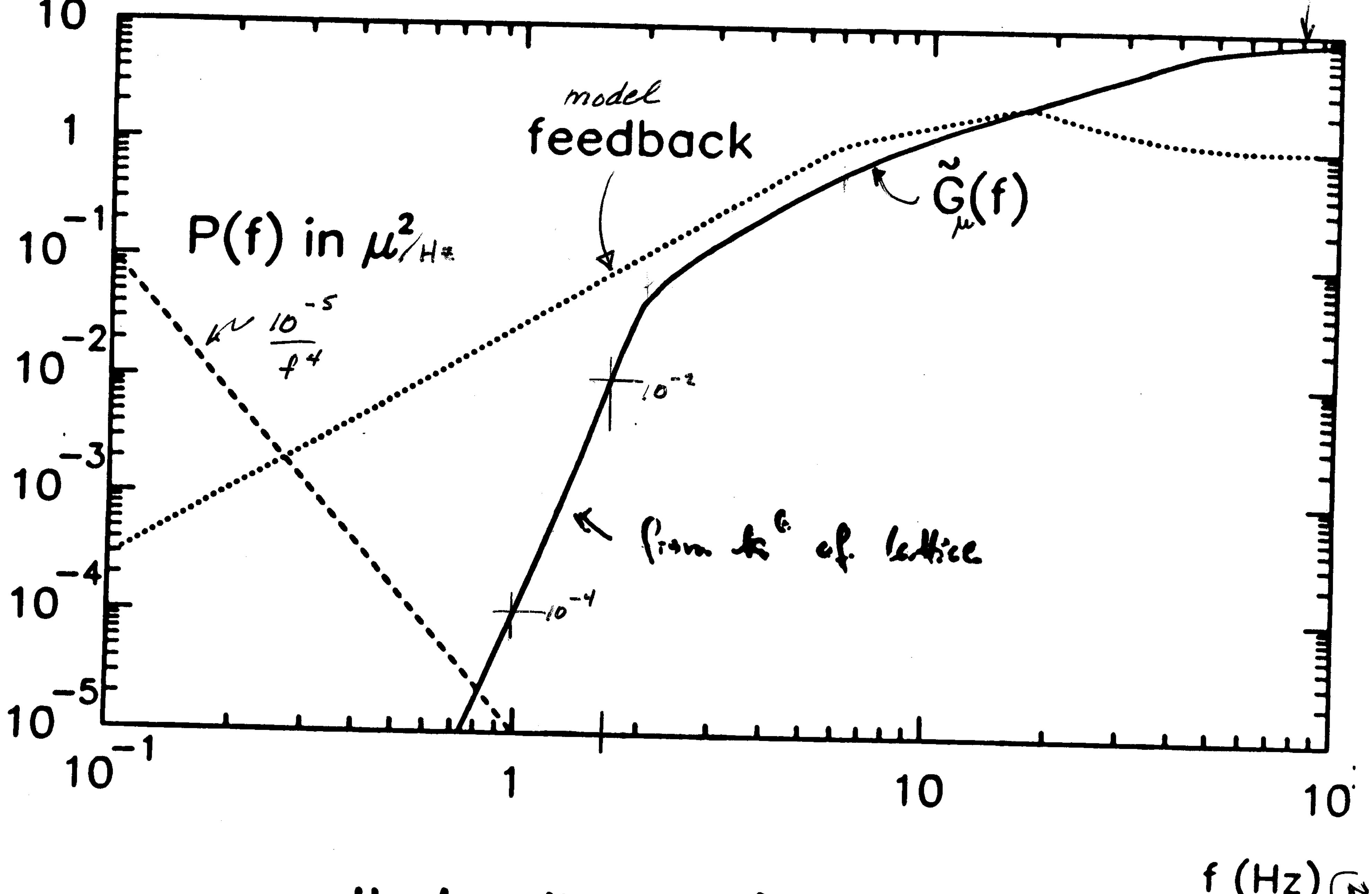
$$= \int_0^\infty P(\omega)\, G_\mu(\omega)\, \frac{d\omega}{2\pi}$$

If there is suppression of low freq. by a feedback system.

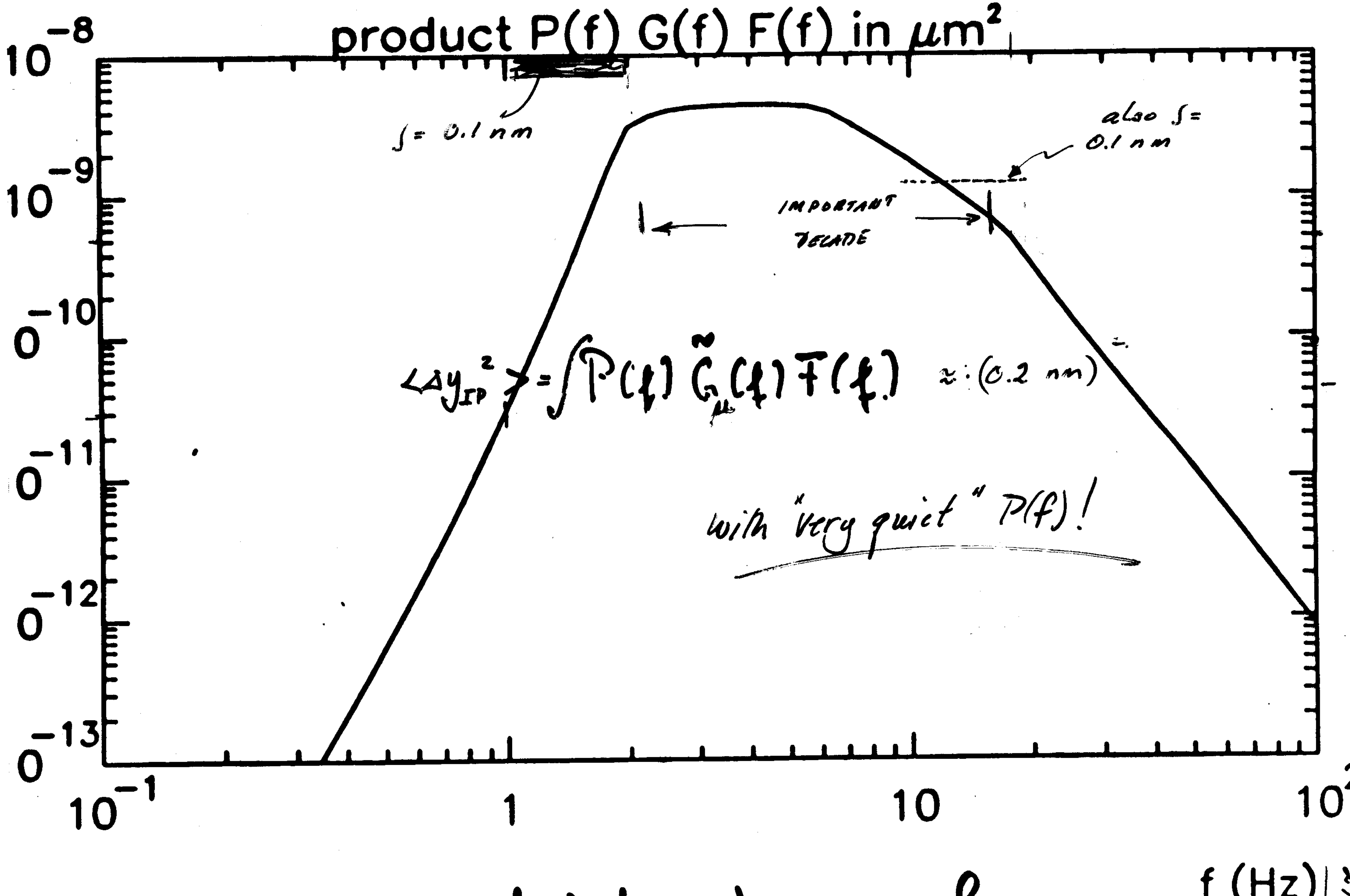
$$\boxed{\langle \Delta y_B(t)^2 \rangle_t = \int_0^\infty P(\omega)\, G_\mu(\omega)\, F(\omega)\, \frac{d\omega}{2\pi}}$$

5. NLC Feedback with imperfect cascade (Linda Hendrickson)





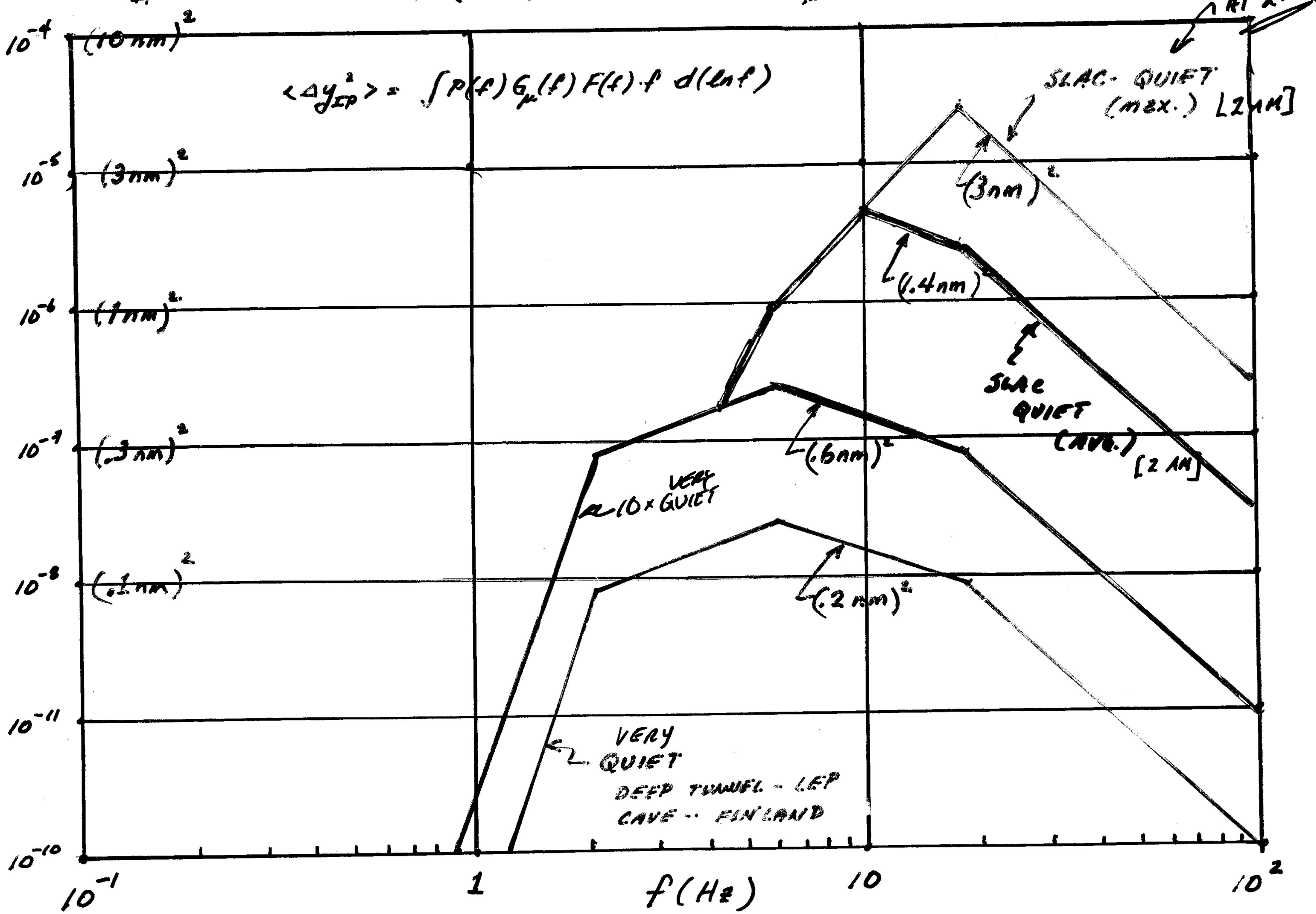
multiply these 3 functions



... and integrate over f ...

$$G_\mu(f) = \int G(k)\,\mu(\omega, k)\,\frac{dk}{2\pi}$$

PRODUCT $P(f) \cdot G_\mu(f) \cdot F(f) \cdot f$



4 ← IMPORTANT DECADE → 40

INSTRUMENT & QUADS

$$\frac{\Delta \mathcal{L}}{\mathcal{L}} = \frac{1}{16} \frac{\langle \Delta y_{IP}^2 \rangle}{\sigma_y^2}$$

MY FAVORITE STRATEGY FOR IP REGION

[ASSUMING FINAL QUADS INSIDE DETECTOR]

I. RESONANCES

FINAL QUADS IN A "TUBE"

→ SYSTEM HAS RESONANT FREQUENCIES

TIME OF GROWTH $\tau_{damp} \gg \frac{2\pi}{\omega_n}$

→ STEERING (DEFLECTION!) BY OFFSET BEAMS IS VERY STRONG & EASILY MEASURED.

FILTER FOR RESONANT MODES

→ STEER BEAM TO NULL SIGNAL — (at ω_n's)

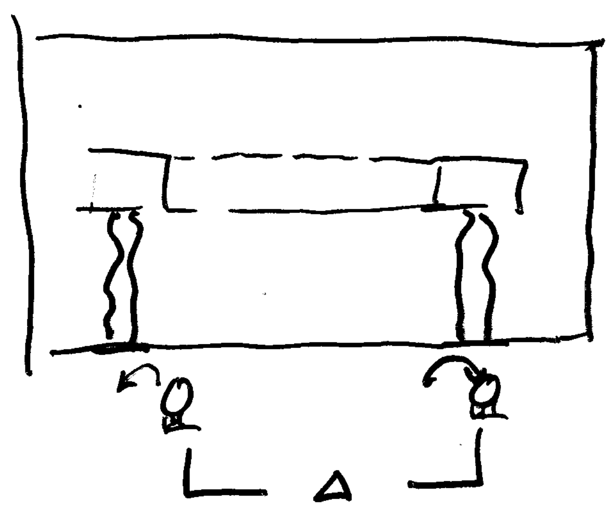
PRESUMABLY THIS TAKES CARE OF VIBRATION SOURCES W/IN DETECTOR —

II. ANTI-SYMMETRIC "BEAM" MOTION

— NON-RESONANT —

PRESUMABLY DUE TO GROUND MOTION

- MEASURE ANTI-SYMMETRIC GROUND MOTION AT "SOURCE"
  - BASE OF DETECTOR -



- DEDUCE SUPPORT BEAM (NON-RESONANT) MOTION
  - MODEL
  - MEASUREMENTS
  > ADAPTIVE PARAMETERS -!

- COMPENSATE w/ BEAM STEERING

EXTERNAL QUADS NEAR IP... LIKEWISE

CONCLUSIONS

1) $P(\omega)$ VARIES A LOT —

- DEEP TUNNELS DRAMATICALLY BETTER IN CRUCIAL REGION.
- & LESS SUSCEPTIBLE TO CHANGES IN "CULTURAL" BACKGROUNDS

2) $\mu(\omega,k)$ MAY BE CONSTANT — CHECKS?

3) $\mu(\omega,k)$ WELL-FIT w/ UNIFORM WAVES AT SOME $v(\omega)$. CHECKS

4) LIMITS CAN BE PLACED ON ATL COEFF IN THIS FREQ. RANGE –

5) AT DEEP - VERY QUIET SITES ~ GROUND MOTION $\langle \Delta y_{IP}^2 \rangle \sim (0.2\,nm)^2$ IS ACCEPTABLE

A SURFACE SITES — NOT ACCEPTABLE W/O FURTHER INTERVENTION!