HEARING THE ν's

PROSPECTS FOR ACOUSTIC DETECTION OF COSMIC NEUTRINOS

deja vu but
- NEW IMPETUS FROM GZK ν's
- IMPROVEMENTS IN TECHNOLOGY
- ν TELESCOPES UNDER CONSTR – SMALL ADD.
- A HINT IN BAIKAL ?

- REVIEW THEORY & CALCULATIONS
- EXPERIMENTAL TESTS BNL, HARVARD, LSU, RUSSIA
  ONE ANOMALY 
- PROSPECTS
  - DEEP OCEAN UHE ν's w/ ν CHER.TEL
  - EAS
  - WHOLE OCEAN SEARCH FOR SHE ν's
- CONCLUSION: TIME FOR A NEW LOOK

WHAT IS THE DOMAIN OF ACOUSTIC ν DET.?

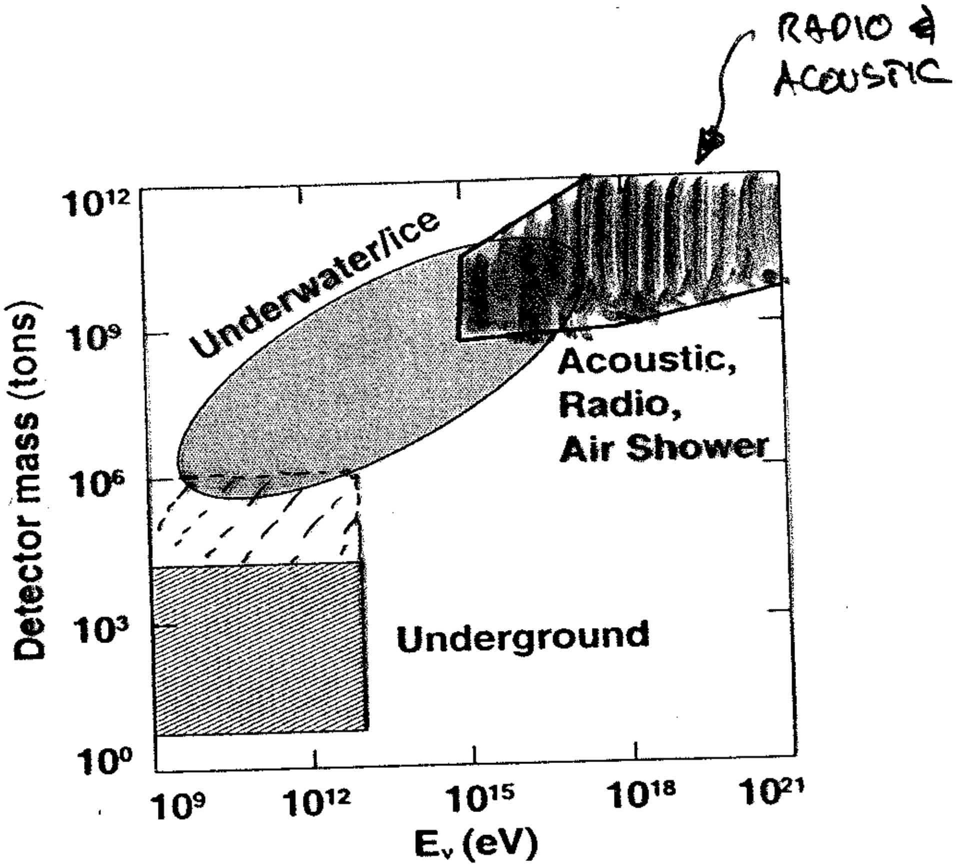


Figure 1. Domains of different detection techniques.

(FROM SPIERING @ NU2000)

$E_\nu \gtrsim 10^{16}$ eV

$V \gg 1\ \mathrm{km}^3$

ACOUSTIC DETECTION UNDERWATER ~~IN DUMAND~~
INTRODUCTION

ATTRACTIONS

→ ① LONG DIST. DETECTION ⇒ <u>LARGE DET. VOL'S.</u>

- a) $\frac{\lambda^{\text{ACOUST}}_{\text{ATTEN}}}{\lambda^{\text{OPT}}_{\text{ATTEN}}} \gg 1$
- b) ACOUST RAD IS COHERENT & NON-DISPERSIVE
- c) DIST. DEPENDANCE IS POWER LAW

$$P(r) \propto \frac{1}{\sqrt{r}} \rightarrow \frac{1}{r} \rightarrow \frac{1}{r^2}$$

$$\left(L(r) \propto \frac{1}{r^2} \rightarrow \frac{1}{r^2} e^{-r/\lambda} \right)$$

② TECHNOLOGY WELL KNOWN

- a) LONG HISTORY OF SONAR WORK
- b) RAPID PROGRESS IN PROCESSING
- c) INEXPENSIVE COMPONENTS

③ BACKGROUND NOISE LOW AT DEPTH

⋮

PROBLEM

→ ① <u>SMALL INHERENT SIGNAL/NOISE RATIO</u>

⇒ HIGH THRESHOLD ENERGY

- a) INEFFICIENT MECHANISM $\sim 10^{-9}$
- b) LENGTH OF CASCADE
- c) OCEAN NOISE

⋮

PRODUCTION OF SOUND PULSES BY CHARGED PARTICLES IN LIQUIDS

QUICK REVIEW OF THEORY:

- FIRST REFERENCE ASKARIAN (USSR) ~ 1958
- PRESENT APPLICATION BOWEN (1975 MUNICH)
- DUMAND 1976 WORKSHOP BOWEN ≈ 10^6 × DOLGOSHEIN
- SPRING 1977: BOWEN REVISED (MN-73)
  LEARNED SIMPLE THEORY
  OTHERS

MECHANISMS: ✓ 1) THERMOACOUSTIC

× 2) MICROBUBBLES

× 3) OTHERS (MOM. XFER, MOLECULAR PHEN, CER. RAD., ----)

1) PARTICLE IONIZATION → HEATING (INSTANTANEOUS)

→ EXPANSION → ACOUSTIC RADIATION

SIMPLE THEORY:

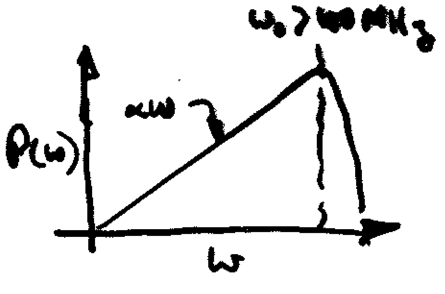
→ a) ONE SHOULD WORK IN TIME DOMAIN

→ b) PULSE SHAPE DOMINATED BY THE MEDIUM AT ALL REASONABLE DISTANCES (eg > mm)

→ c) CONSTRUCT MICROPULSE THEN ADD THESE FROM AN ENSEMBLE OF POINTS

MICRO PULSE

$p(t)$:  $\frac{\partial}{\partial t}\delta(t-t_0)$



WAVE EQN WITH ATTENUATION

- $\rho_0 \dot{u}_x = -\frac{\partial P_e}{\partial x}$ EQN OF MOTION (F = ma)
- $\rho_0 \frac{\partial u}{\partial x} = -\dot{\rho}_c$ EQN OF CONTINUITY (CONS OF PARTICLES)
- $P_c = \rho_c \frac{K_s}{\rho_0} + \overset{\text{VISCOSITY TERM}}{\overset{\downarrow}{\dot{\rho}_c \frac{\xi}{\rho_0}}}$ EQN OF STATE (STOKES)

$$\rightarrow \boxed{\nabla^2 \left[p + \frac{1}{\omega_0} \dot{p} \right] - \frac{1}{c_0^2} \ddot{p} = 0}$$

$\omega_0 \approx 1670$ GHz for water $= K_s/\xi$

$c_0 \approx 1.5$ mm/μs $= \sqrt{K_s/\rho_0}$

$$c = c_0 \left[1 + \cancel{\frac{5}{8}\left(\frac{\omega}{\omega_0}\right)^2} + \ldots \right] \approx \text{CONST} \sim \text{NON-DISPERSIV}$$

$$\alpha = \frac{\omega^2}{2\omega_0 c} \left[1 - \frac{5}{8}\cancel{\left(\frac{\omega}{\omega_0}\right)^2} + \ldots \right] \propto \omega^2$$

- IN MOST LIQUIDS

$\boxed{\text{ATTEN} \propto f^2}$ => EFFECT OF DISTANCE IS LIKE CONVOLUTION WITH A GAUSSIAN (WHOSE WIDTH GROWS AS $\sqrt{\text{DIST}}$)

$e^{-\alpha \omega^2}$

MACROPULSE (SUM OF MICROPULSES)

DISTRIBUTION

CONVOLUTE $P(r,t) = \int dx\, p(t-x)\, g(x)$

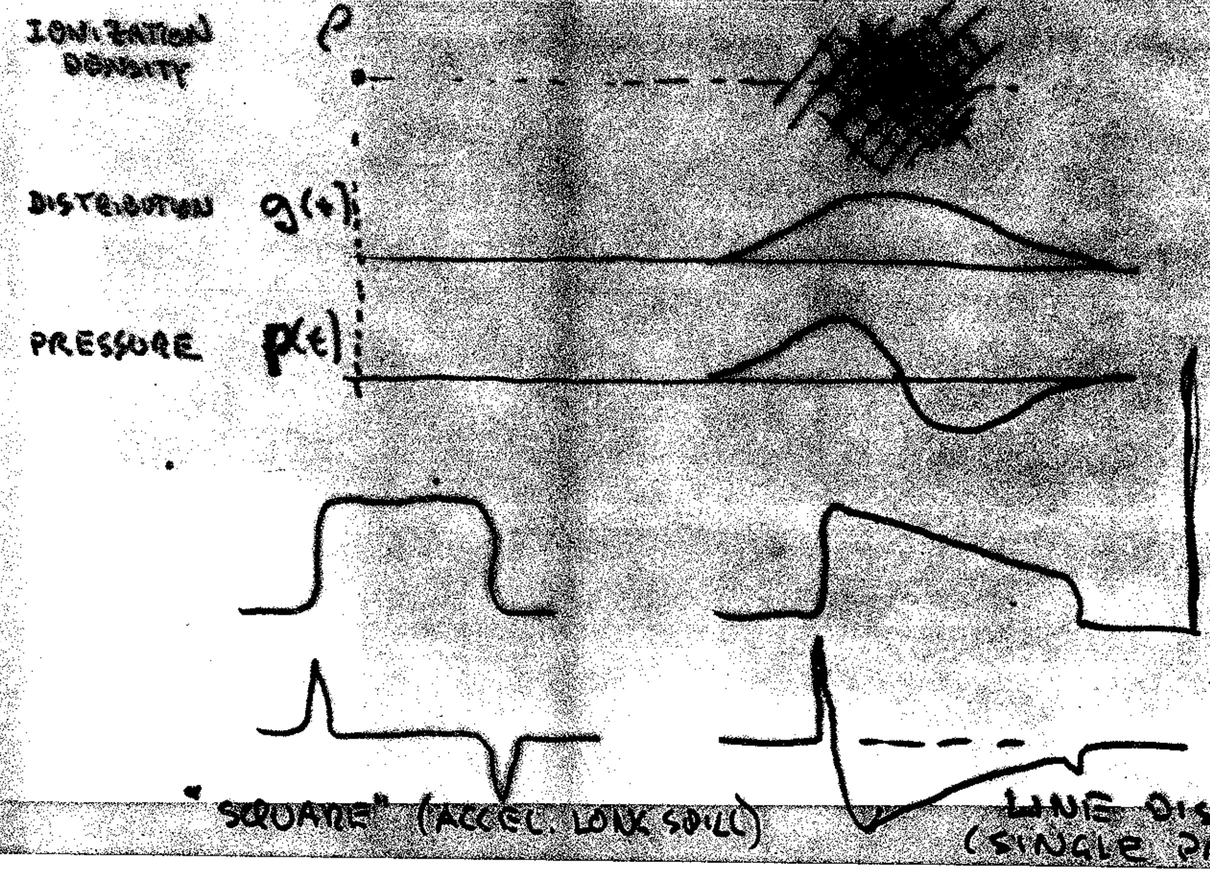
↓

PRODUCT $\mathcal{P}(r,\omega) = P(\omega)\cdot G(\omega) \approx i\,\boxed{\underline{\omega}}\,G(\omega)$

↓

TIME DERIV. $$\boxed{p(r,t) = \frac{E\beta}{4\pi C_p}\frac{\partial}{\partial t}\left[\frac{g(t)}{r}\right]}$$

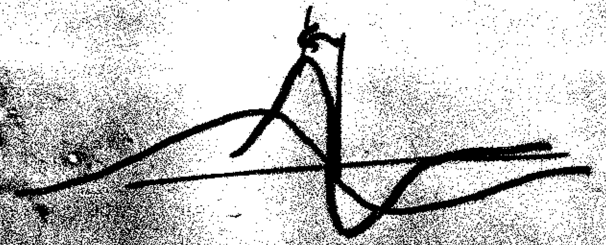
$$g(t) = \int dV \rho(\vec{r})\,\delta(|\vec{r}| - ct)$$



"SQUARE" (ACCEL. LONG SPILL)

LINE DIST. (SINGLE PART'S)

MICROPULSE

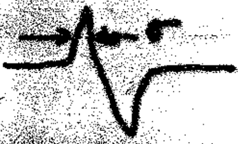


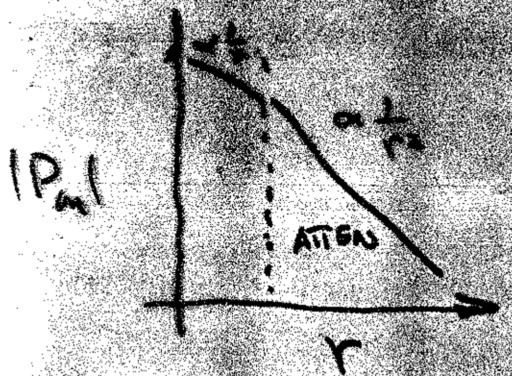
$$p(r,t') = -\frac{2}{\sqrt{\pi}} \frac{E_0\beta}{4\pi C_p} \frac{1}{r} \frac{t'}{8\tau^3} e^{-\left(\frac{t'}{2\tau}\right)^2}$$

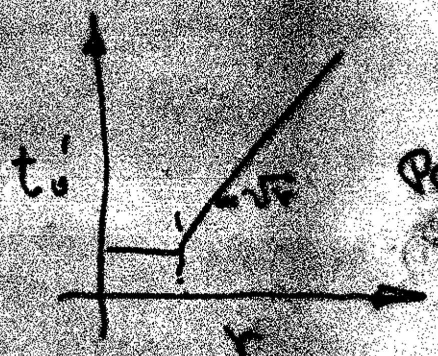
$$\tau = \sqrt{\frac{\sigma^2}{4} + \frac{I}{2\omega_0}} \longrightarrow \sqrt{\frac{I}{2\omega_0}} \propto \sqrt{r}$$

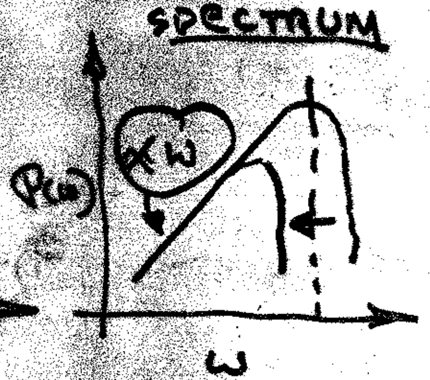
$T = r/c$

$t' = t - T$









- FIRST ORDER SOL'N TO STOKES EQN
- <u>INDEPENDANT OF THERMOACOUSTIC</u> DETAILS AT REASONABLE DISTANCES
- DETAILED THEORIES HAVE TROUBLES ANYWAY (SHOCK WAVES? CONTINUOUS MEDIA? EQN OF STATE? MOLECULAR PHENOMENA?....). IN THIS "THEORY" WE ONLY NEED MEASURE THE NORMALIZATION.

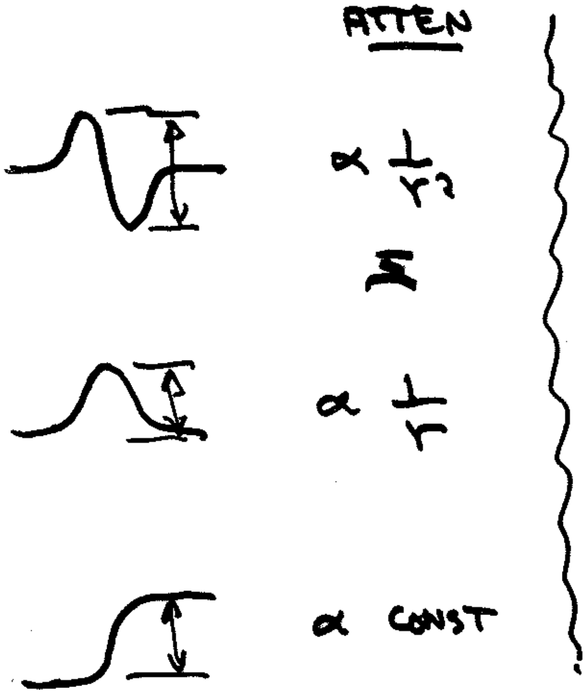
AS A RESULT OF ① THE $e^{-\frac{\omega^2}{\omega_0^2}}$ ATTENUATION

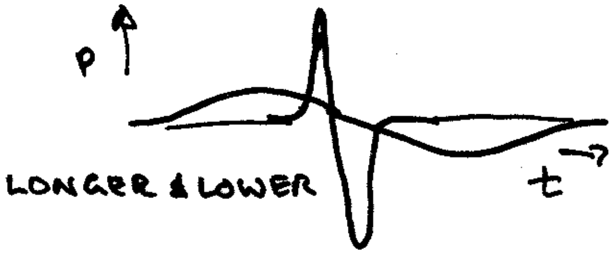
AND ② THE BIPOLAR PULSE

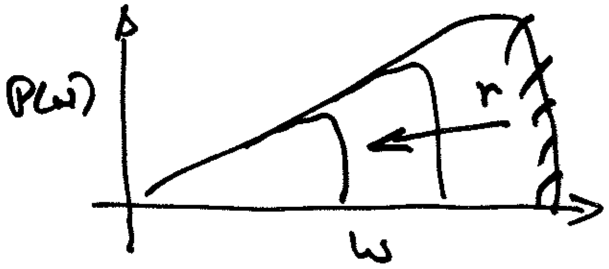
THE DISTANCE DEPENDANCE IS POWER AT ALL DISTANCES

eg $P_m(r) \propto \frac{1}{\sqrt{r}} \to \frac{1}{r} \to \frac{1}{r^2}$ FOR CASCADE

NEAR FAR ATTEN



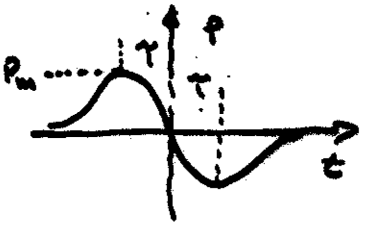




[NAIVELY ONE EXPECTS EXPONENTIAL DEPENDANCE IN ATTENUATION ZONE]

FOR GAUSSIAN DISTRIBUTIONS:

$$P(t) = \frac{1}{\sqrt{2\pi}} \frac{1}{r} \frac{E\beta}{4\pi C_p} \frac{t}{\tau^3} e^{-t^2/2\tau^2}$$



$$P_m = \frac{1}{\sqrt{2\pi e}} \frac{E\beta}{4\pi C_p} \frac{1}{r} \cdot \frac{1}{\tau^2}$$

MAX PRESSURE $$\boxed{P_m = 7.38 \times 10^{-26} \frac{E\,(eV)}{r\,(cm) \times [\tau\,(sec)]^2} \; \overset{10^{15}\,\mu Pa}{dynes/cm^2}}$$

(FOR SALT WATER AT 4°C OR FRESH WATER AT 11°C)

OBS. DIST.

$\tau = \frac{\sigma}{c}$ = "SIZE" OF DEPOSITION REGION

TO COMBINE SPACE & TIME DISTRIBUTIONS:

CONVOLUTE DISDRIBUTIONS

$$\boxed{P_m \approx 170\,\mu Pa \frac{E/10^{17}\,eV}{r/1\,Km \times [\sigma/1\,cm]^2}}$$

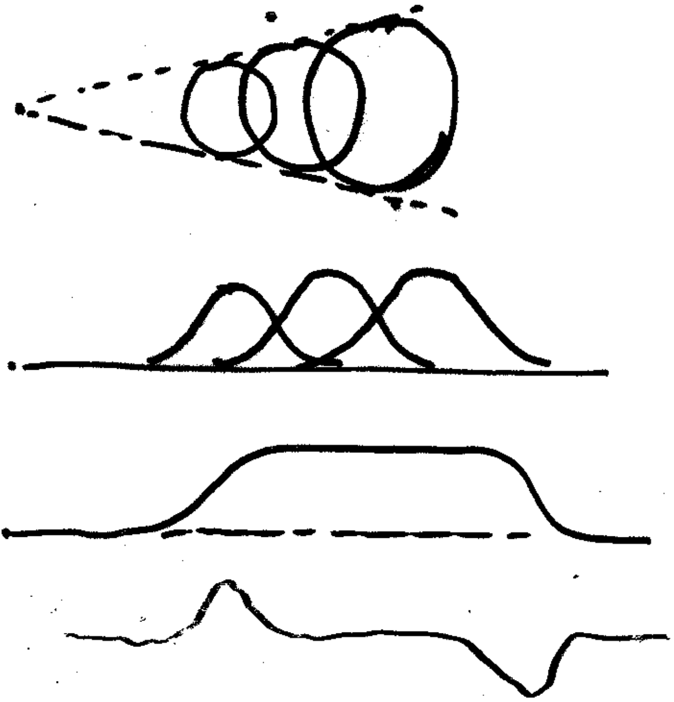
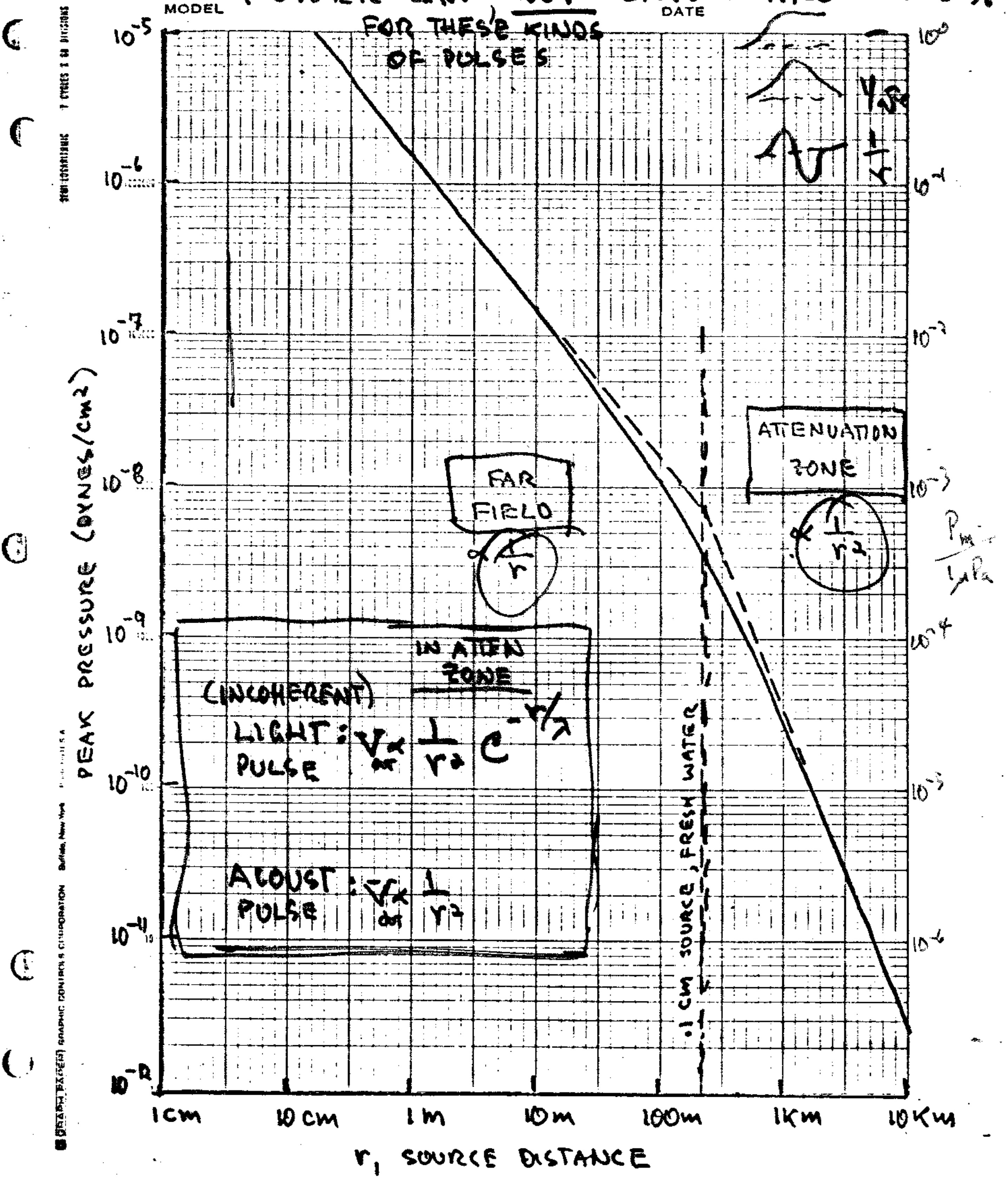


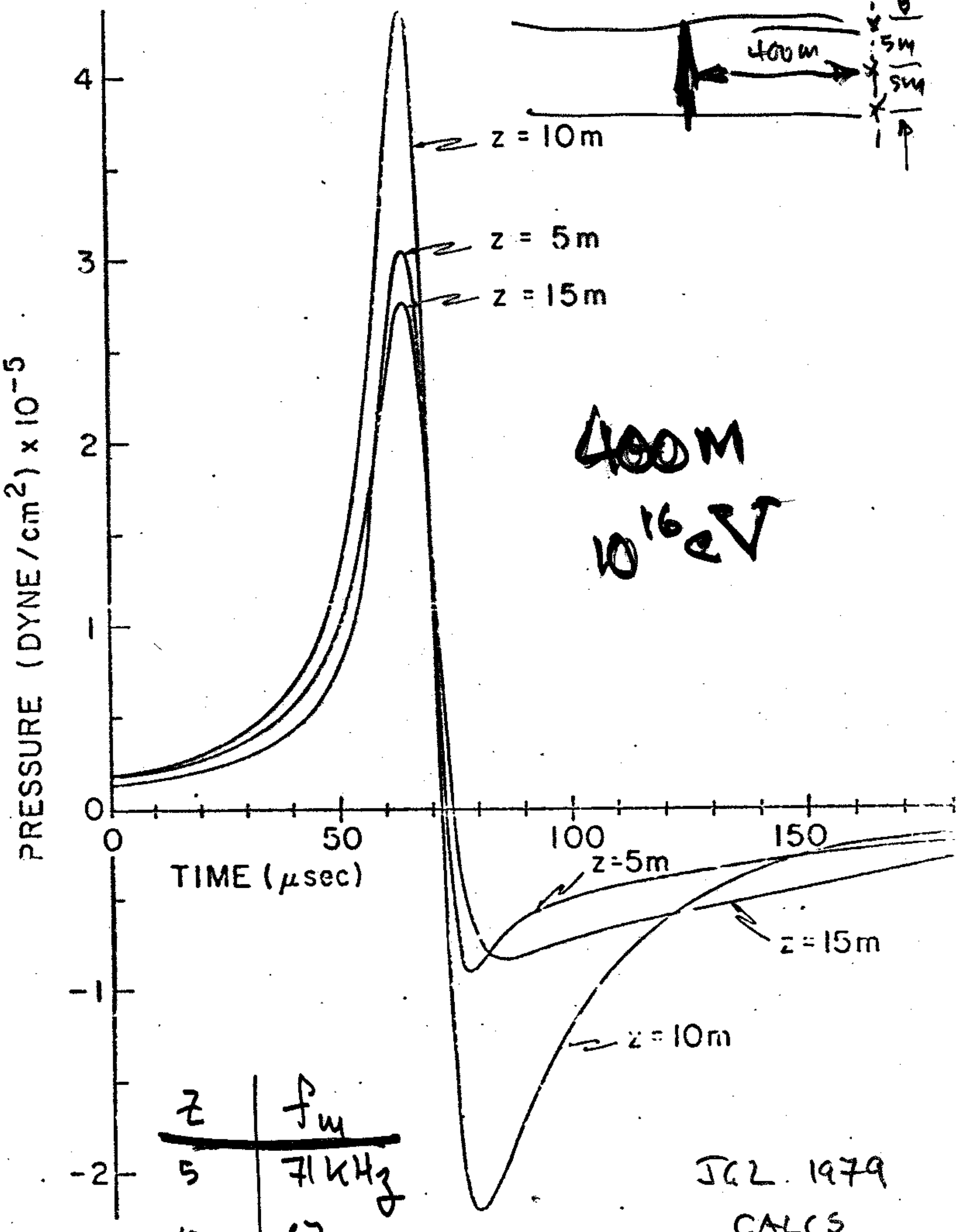
Fig. 1 ©

ATTENUATION PRODUCES A POWER LAW NOT EXPON FALL WITH DIST FOR THESE KINDS OF PULSES



ACOUSTIC PULSE FROM A CASCADE

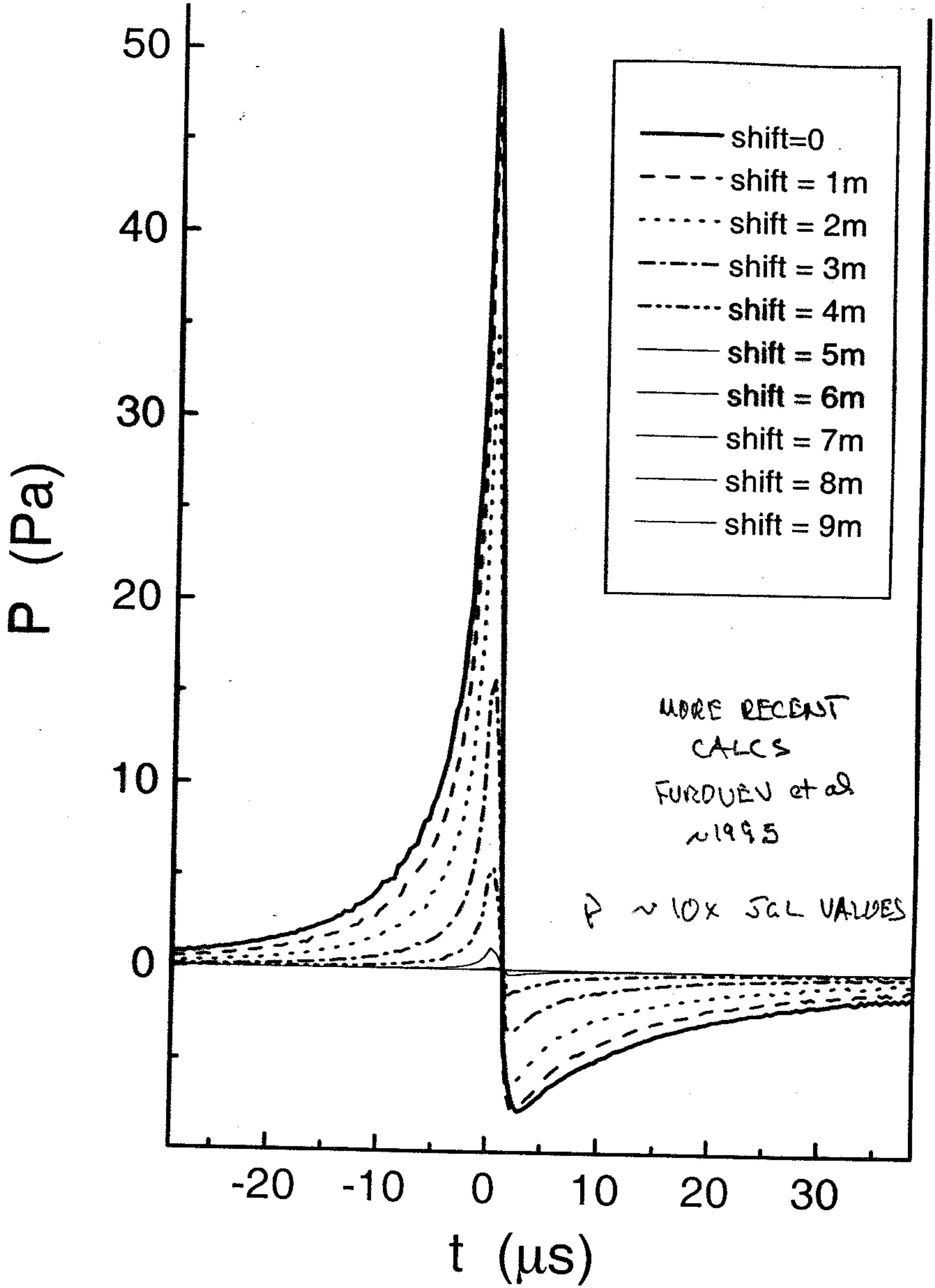
Figure 4:



400M
10^{16}eV

z	f_M
5	71 kHz
10	67
15	48

JGL 1979
CALCS



MORE RECENT
CALCS
FURDUEV et al
~1995

P ~ 10x JGL VALUES

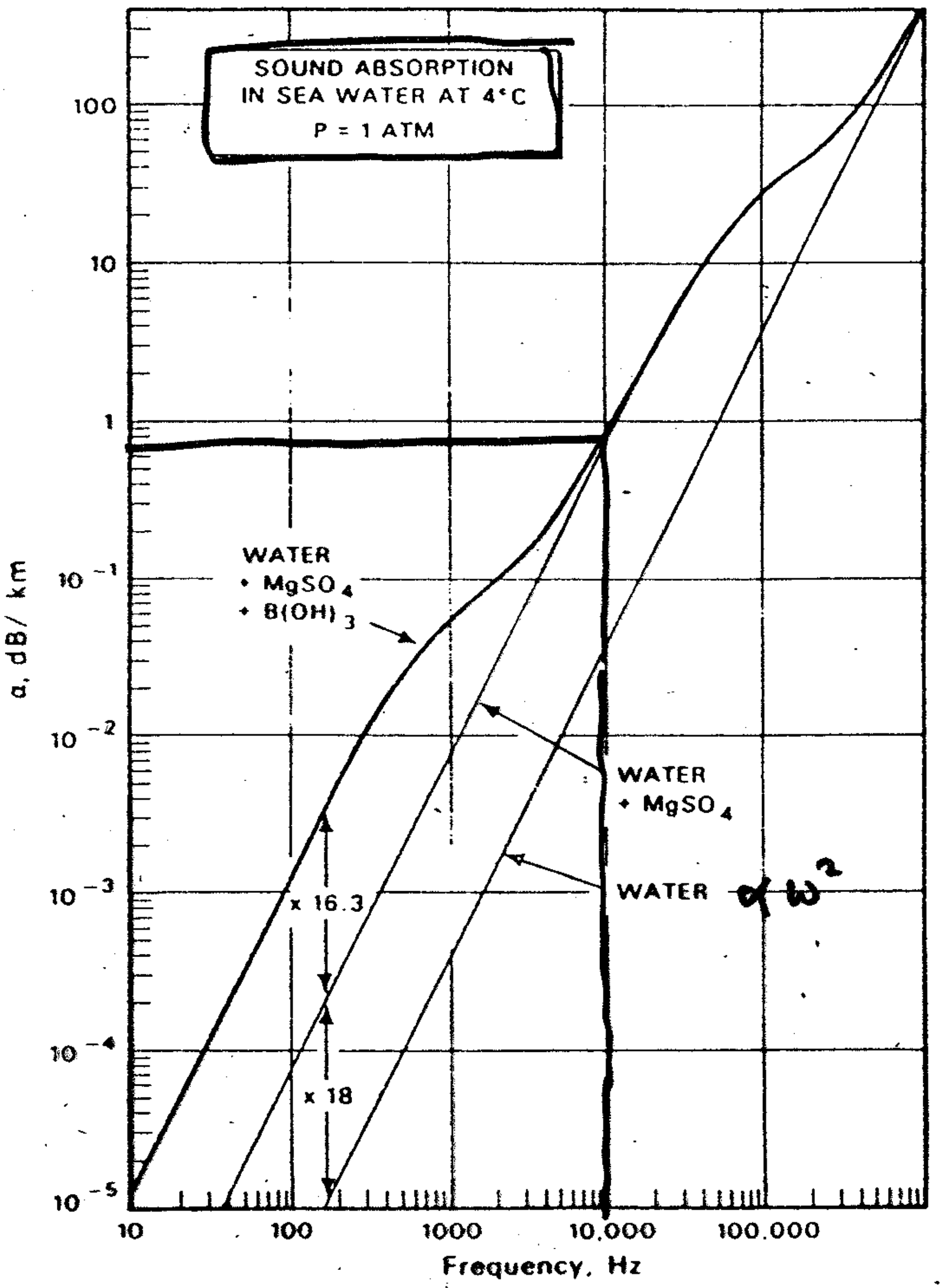
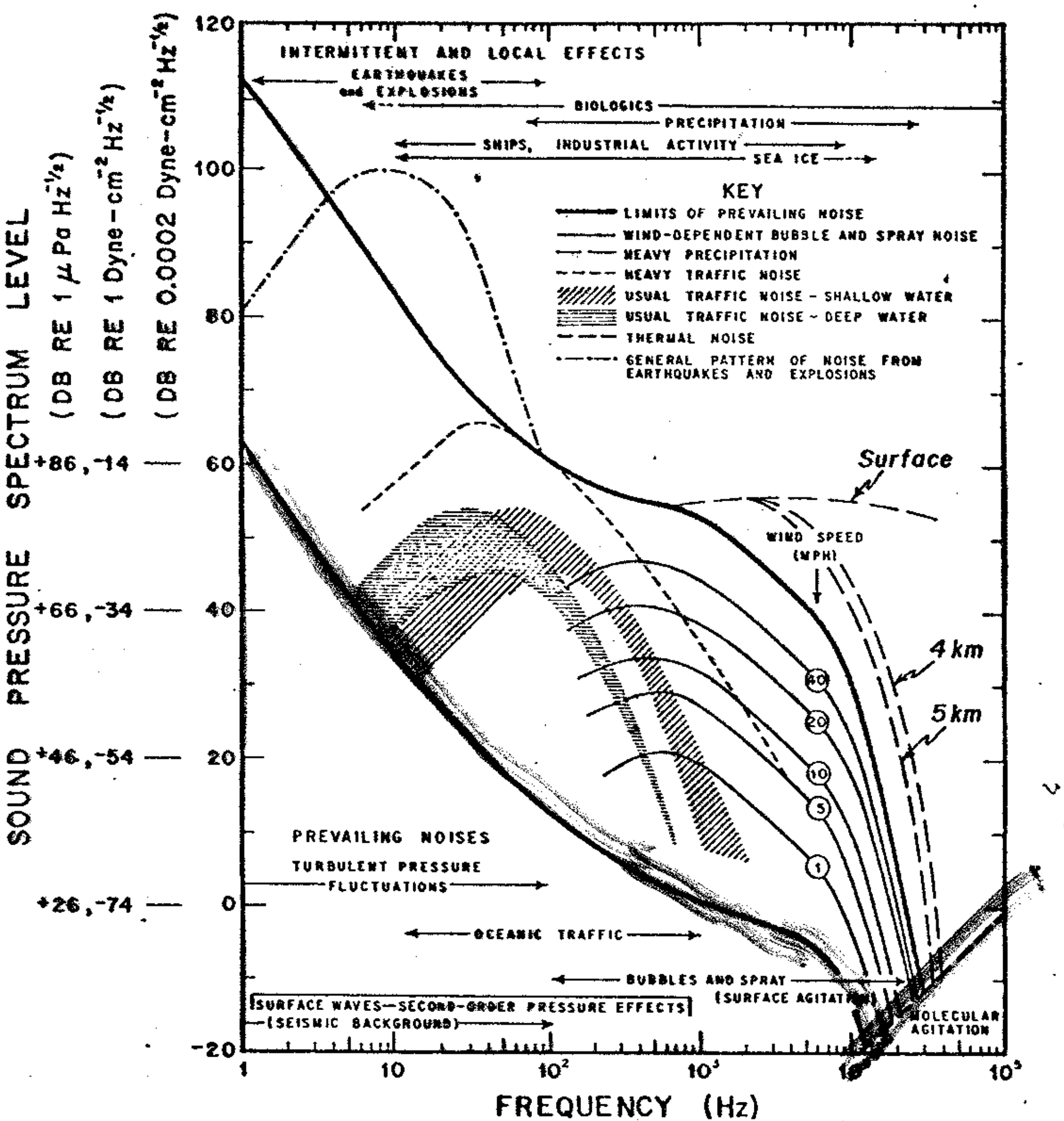


FIG. 1. Sound absorption in Lyman and Fleming sea water of salinity $= 35\,{}^{0}/_{00}$ and $pH = 8.0$. These curves were calculated from laboratory acoustic measurements by Simmons from 6 to 350 kHz in a 200-liter spherical resonator.

F. H. Fisher and V. P. Simmons

J. Acoust. Soc. Am., Vol. 62, No. 3, September 1977

OCEAN NOISE



√ DEEP OCEAN

↑ ν CASCADES

Surface-generated Sound Pressure at 4 & 5 km depth.

Adapted from near-surface curves of Wenz, JASA 34, p1936, (1962)

HB · ~~Mar~~ Apr '77

THE VELOCITY OF SOUND DEPENDS UPON DEPTH IN THE OCEAN

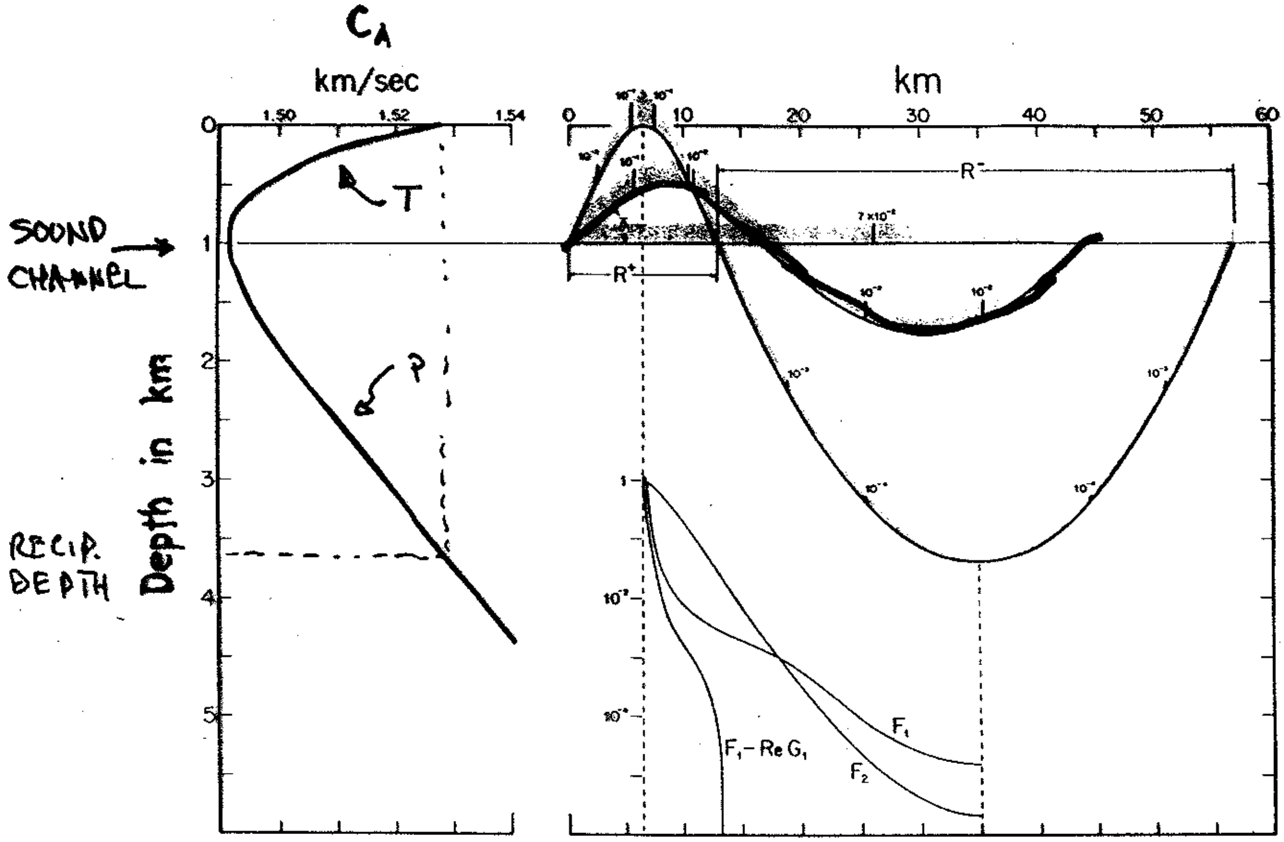


FIG. 1. Canonical sound channel (left) and the corresponding rays for $\bar{\theta} = 12.7°$ (surface limited), 5.2°, and 0° (axial ray). The contribution to F_1 from various parts along the three ray paths is indicated by the vertical extent of the shaded band (plotted logarithmically). F_1 is plotted separately at the bottom of the figure for the surface limited ray, together with F_2 and $F_1 - \mathrm{Re}G_1$, thus indicating the relative apex contributions toward mean-square phase, rate of phase, and intensity. ($F_1 - \mathrm{Re}G_1$ applies only to a source at $x = 0$ of a receiver at R^+.)

- SOUND PROPOGATION OVER ≳ FEW KM IS "VERY INTERESTING"
- MOST NOISE FROM SURFACE (WAVES, SHIPS, CRITTER)
  ⇒ VERY QUIET BELOW RECIPROCAL DEPTH

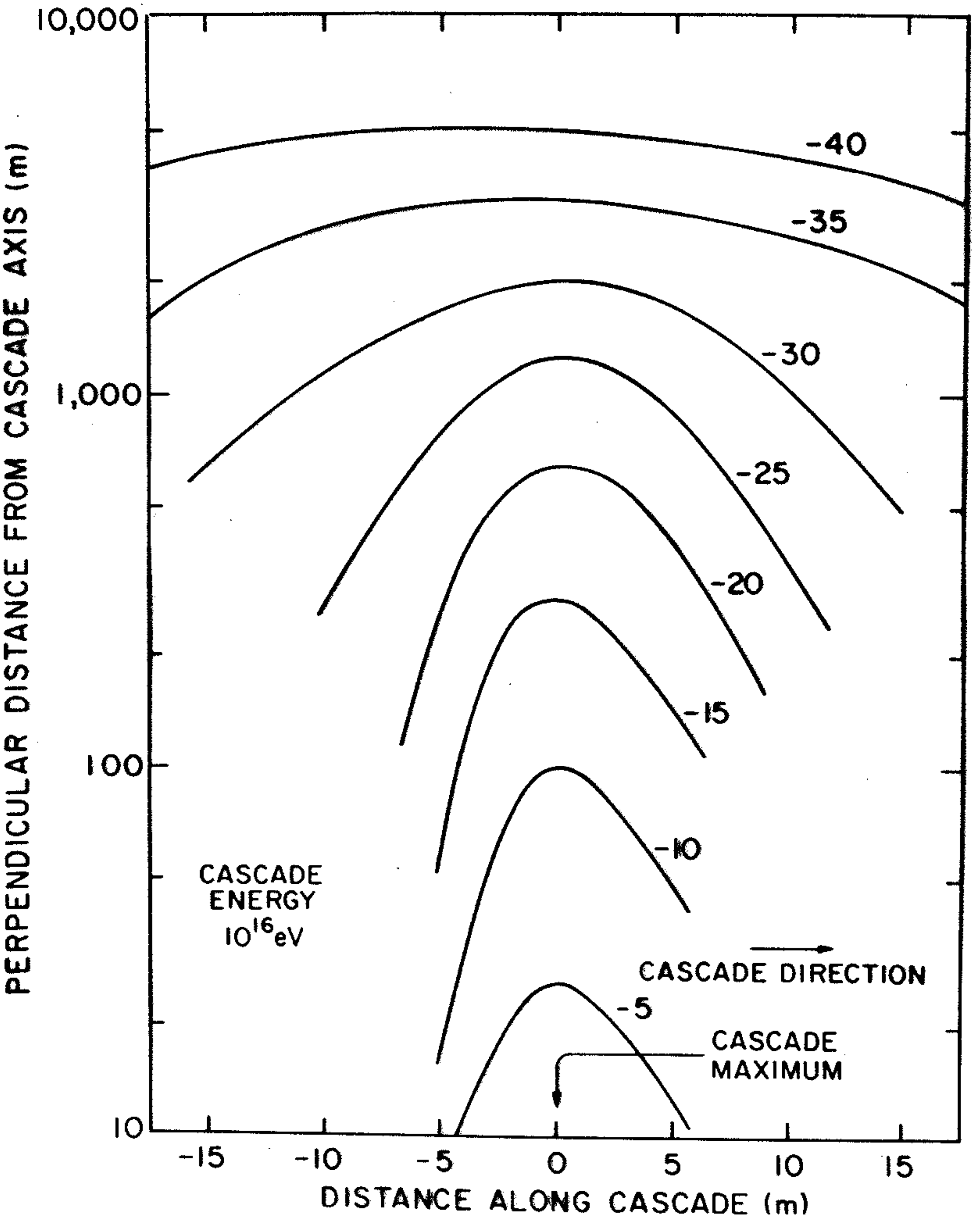
W. H. Munk and F. Zachariasen: Propagation in a fluctuating ocean

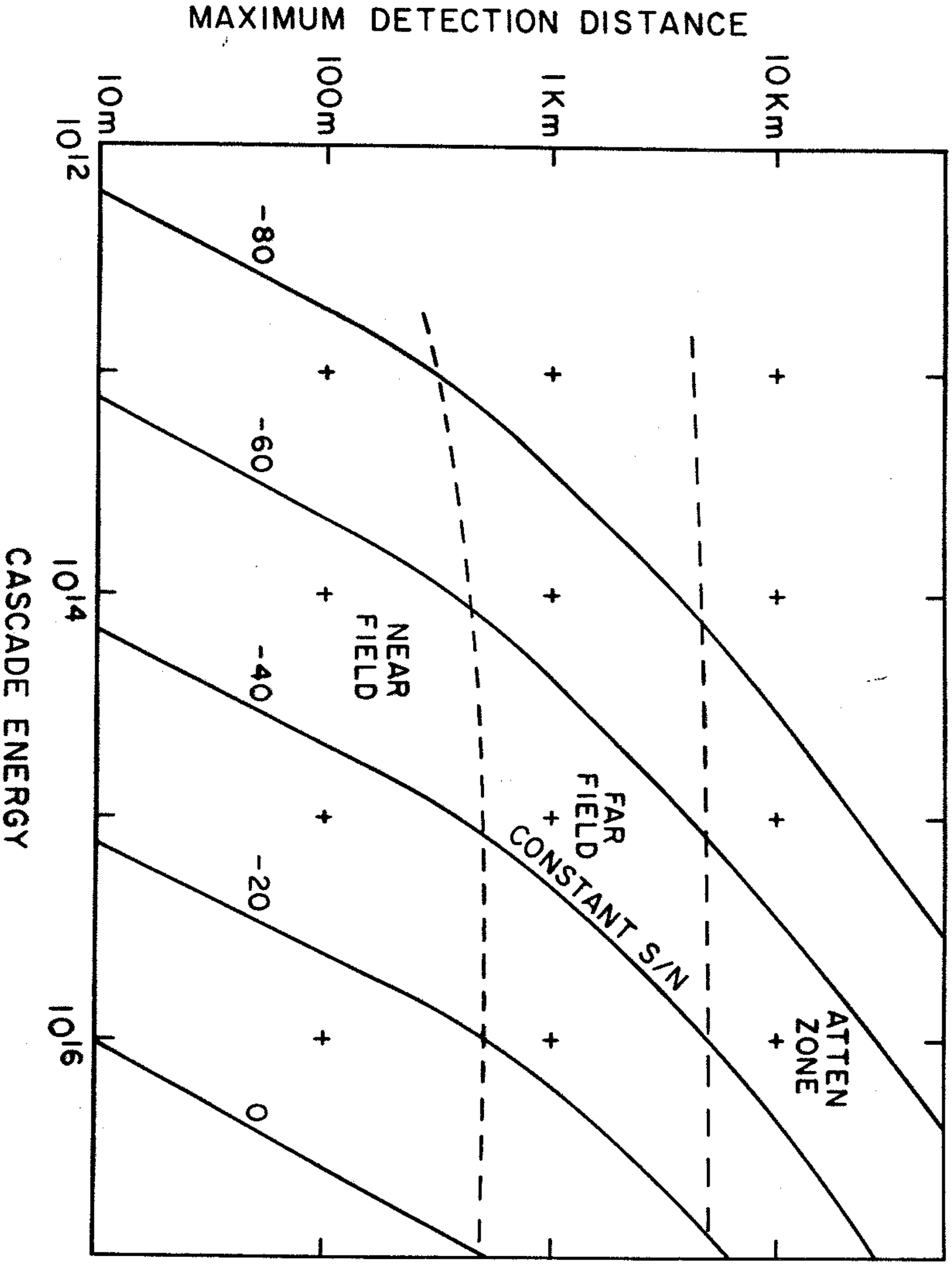
J. Acoust. Soc. Am., Vol. 59, No. 4, April 1976

DEEP OCEAN

MAJOR FACTORS AFFECTING ACOUST TECHNIQUE

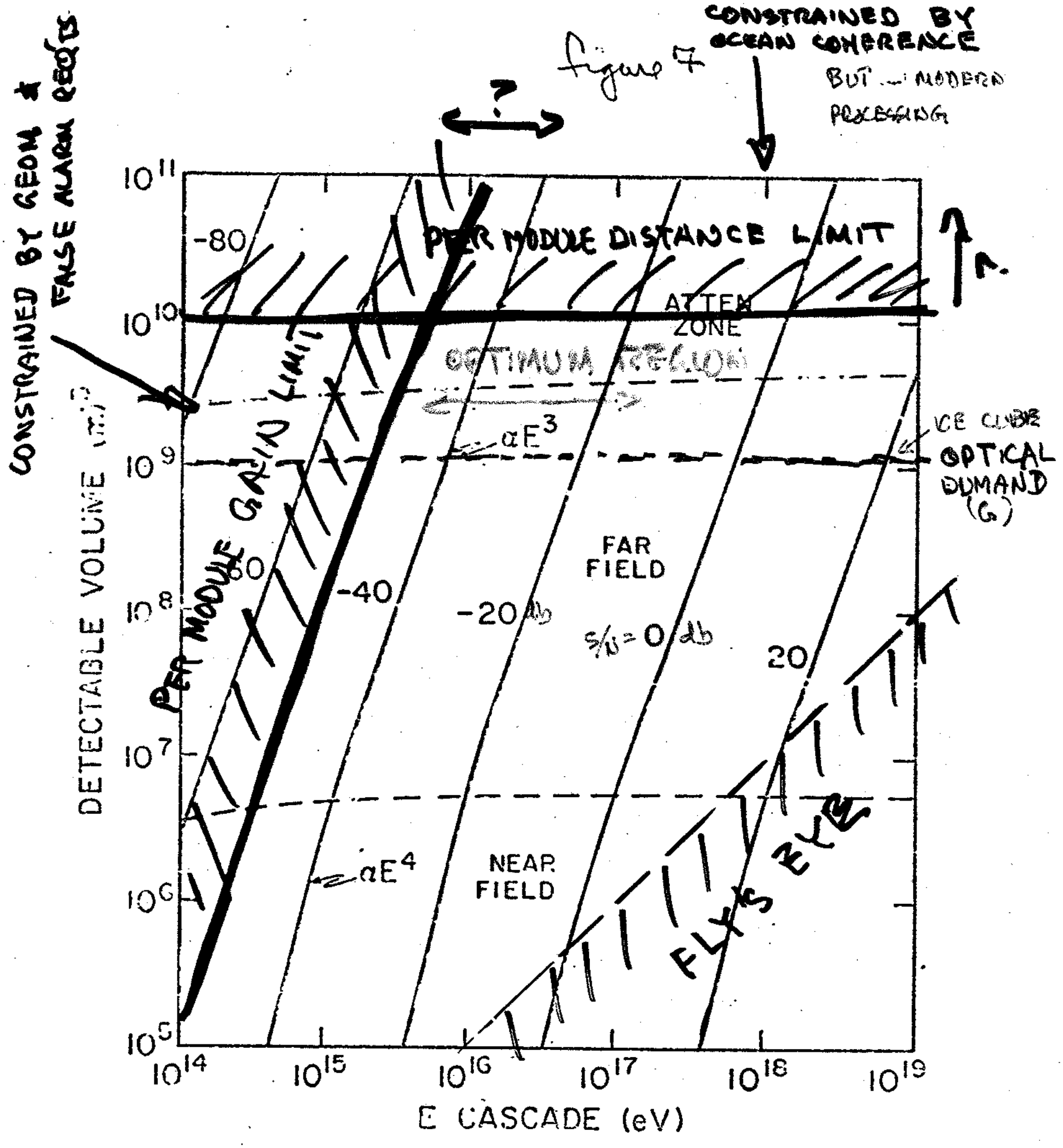
FACTOR	SOURCE	MOST OPTIMISTIC MAGNITUDE	ACTIONS
SIGNAL AMPLITUDE IN THE DEEP OCEAN	- NEW MECH ?	? (SEEMS UNLIKELY)	- LAB TEST BAIKAL TESTS ?
CASCADE DIMENSIONS AT EXTREME ENERGIES (>> 1 TeV)	- RISING σ's - RISING $\langle P_T \rangle$	$E_{TH}/10$ ✓	- MONTE CARLO - LAB STUDIES - DUMAND G
NOISE AT DEPTH	- BETTER THAN ESTIMATES	$E_{TH}/10$ MAYBE WHOLE	- SITE STUDY
TECHNOLOGICAL BREAKTHROUGH	- PROCESSING - HYDROPHONES (FILMS, OPTICS) & ARRAYS	$E_{TH}/100$ SOME	- LAB WORK - WAIT
FLUX OF ν's	- OPTIMISTIC EST. CORRECT - UNEXPECTED	?? GZK CRS @ 10^{20} eV ν's	- THEORIZE - DUMAND G PRELIM ACOUST
σ_ν	- σ_{pp} CONTINUES TO RISE	?? YES	- THEORIZE - DUMAND G - PRELIM ACOUST


10,000
1,000
100
10
PERPENDICULAR DISTANCE FROM CASCADE AXIS (m)
-40
-35
-30
-25
-20
-15
-10
-5
CASCADE ENERGY 10^{16} eV
CASCADE DIRECTION
CASCADE MAXIMUM
-15
-10
-5
0
5
10
15
DISTANCE ALONG CASCADE (m)



MAXIMUM DETECTION DISTANCE
10m
100m
1Km
10Km
10^{12}
10^{14}
10^{16}
CASCADE ENERGY
-80
-60
-40
-20
0
NEAR FIELD
FAR FIELD
CONSTANT S/N
ATTEN ZONE

figure 7

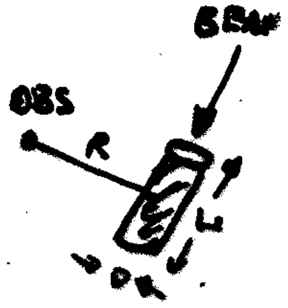


DETECTABLE VOLUME VS ENERGY

EXPERIMENTAL TESTS

✓ BROOKHAVEN 200 MeV LINAC (BLIP)

STOPPING PROTONS
$10^{19} < E < 10^{21}$ eV
$3\mu s < T < 200\mu s$
$D \cong 6$ cm → $40\mu s$
$L \cong 30$ cm (RANGE)
$R > 1$m → 10m

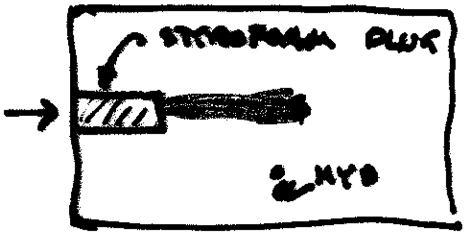


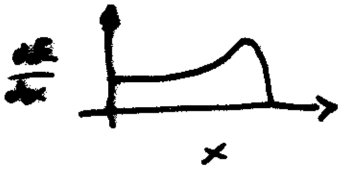
✓ BROOKHAVEN 32 GeV PROTONS (AGS)

MINIMUM IONIZING, THROUGHGOING (30 MeV/PROTON)
$10^{19} < E < 10^{20}$ eV
$T = 2\mu s$
$1 < D < 2$ cm
$L = 16$ cm
$R \simeq 50$cm

✓ HARVARD 160 MeV CYCLOTRON

STOPPING PROTONS
$10^{14} < E < 10^{15}$ eV
$T = 60\mu s$
$D = 2$cm
$L = 17$ cm
$R = 8$ cm





FIRST TRY

LBL 2 GeV/NUCLEON Fe NUCLEI

STOPPING
10^{11} eV (SINGLE NUCLEONS)
$T \approx 0$, $D \approx 1\mu$, $L \leq 30$cm, $R = 1 - 30$ cm

NO SIGNAL ABOVE NOISE

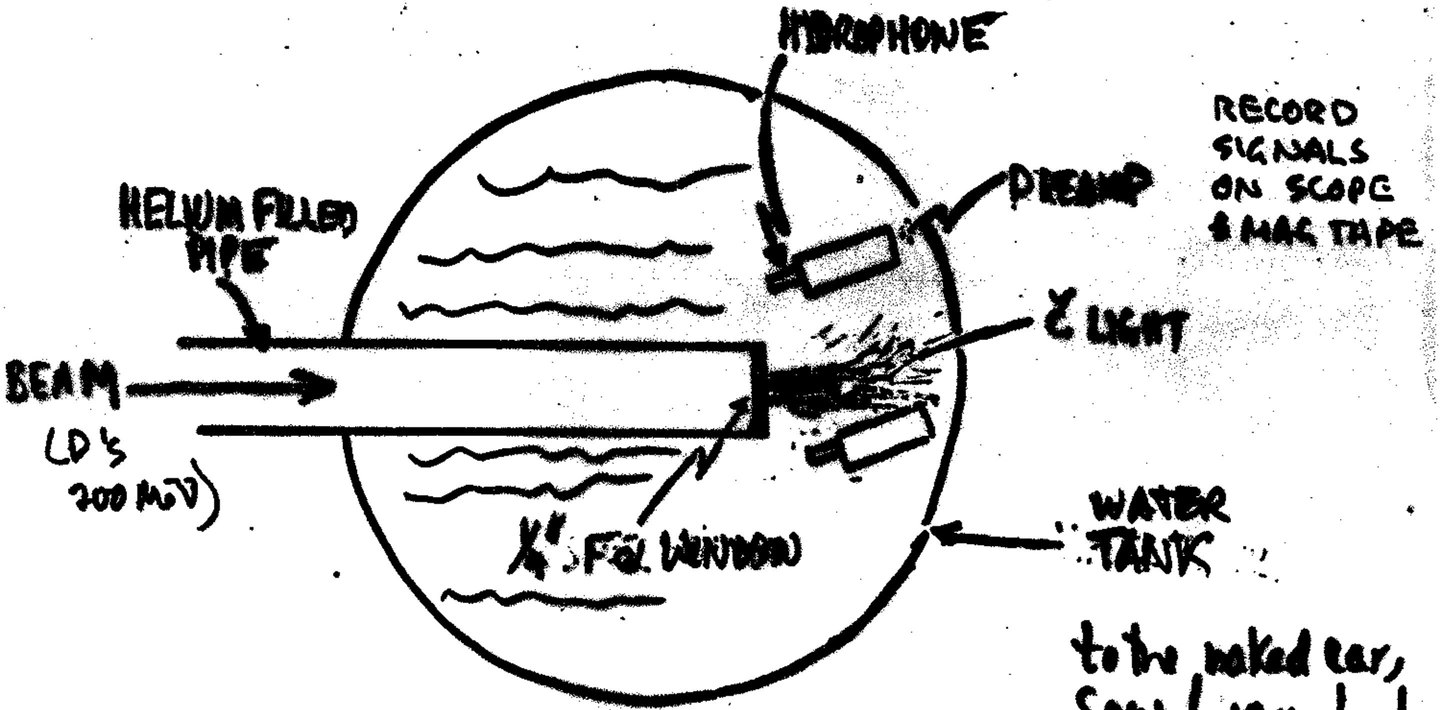
SOON

FNAL ~~<400 GeV PROTONS~~

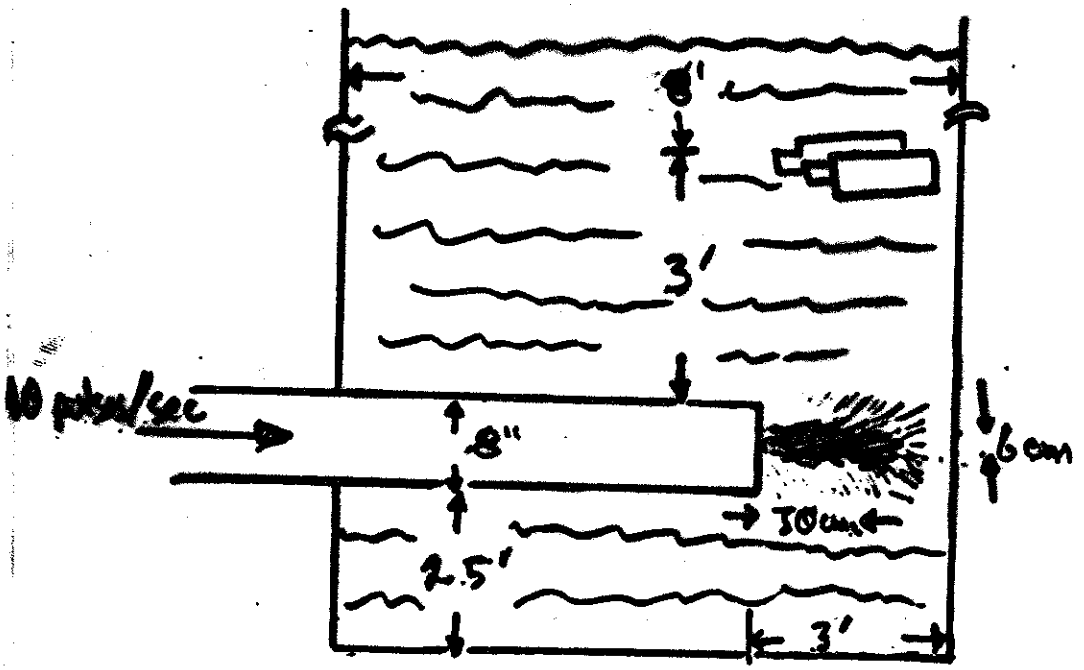
~~THROUGH GOING~~
~~$T = ? < 20\mu s$~~
~~$D \cong 2$cm~~
~~$L = 10$ cm → 10 m~~
~~$R = 1$ → 30 cm~~

DID NOT HAPPEN

BROOKHAVEN 200 MeV LINAC (BLIP)



TOP VIEW



SIDE VIEW

to the naked ear, Sound very loud ... saturates hydrophone for highest depositions

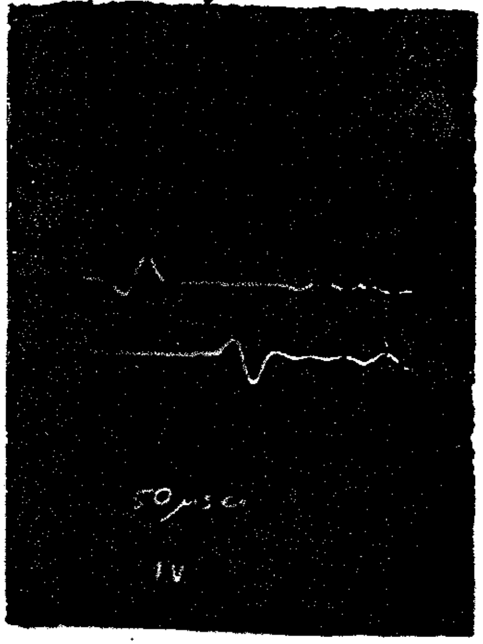
34'

Can hear sound from neutrons

LINAC SIGNAL:

VERY PURE SIMPLE SIGNATURE

$\frac{T}{2}$ = 30μsec = beam diameter/2 ≈ 3cm



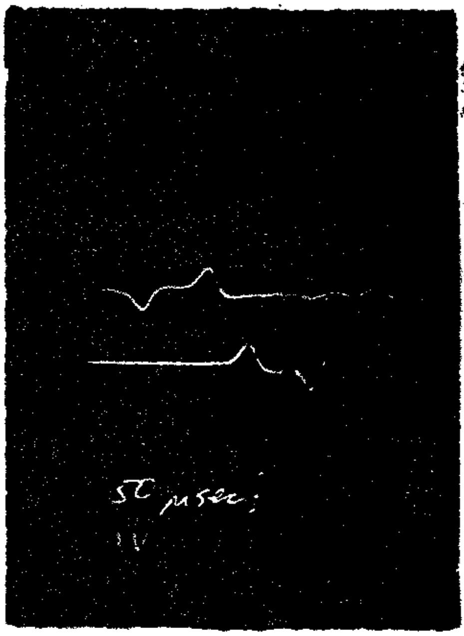
} 2 hydrophones out-of-phase

4ma, 30μsec spill

Compression ↓ rarefaction

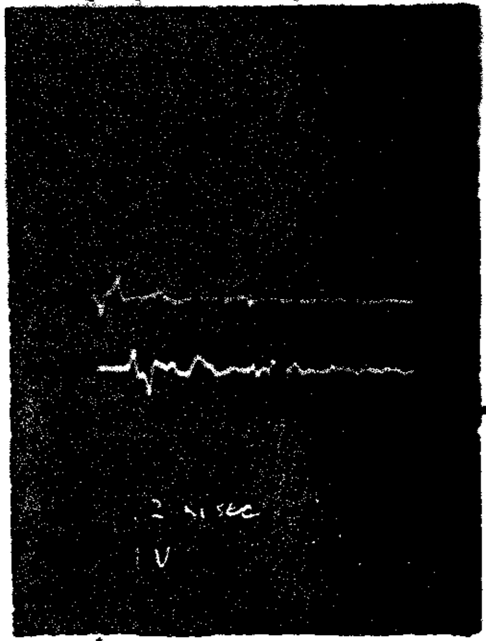
Note time delay between pulses –
3 × 50μsec × 1.5mm/μsec ~ 20cm
= path length difference

Longer Spill – only see signal when $\frac{d}{dt}\rho_0$



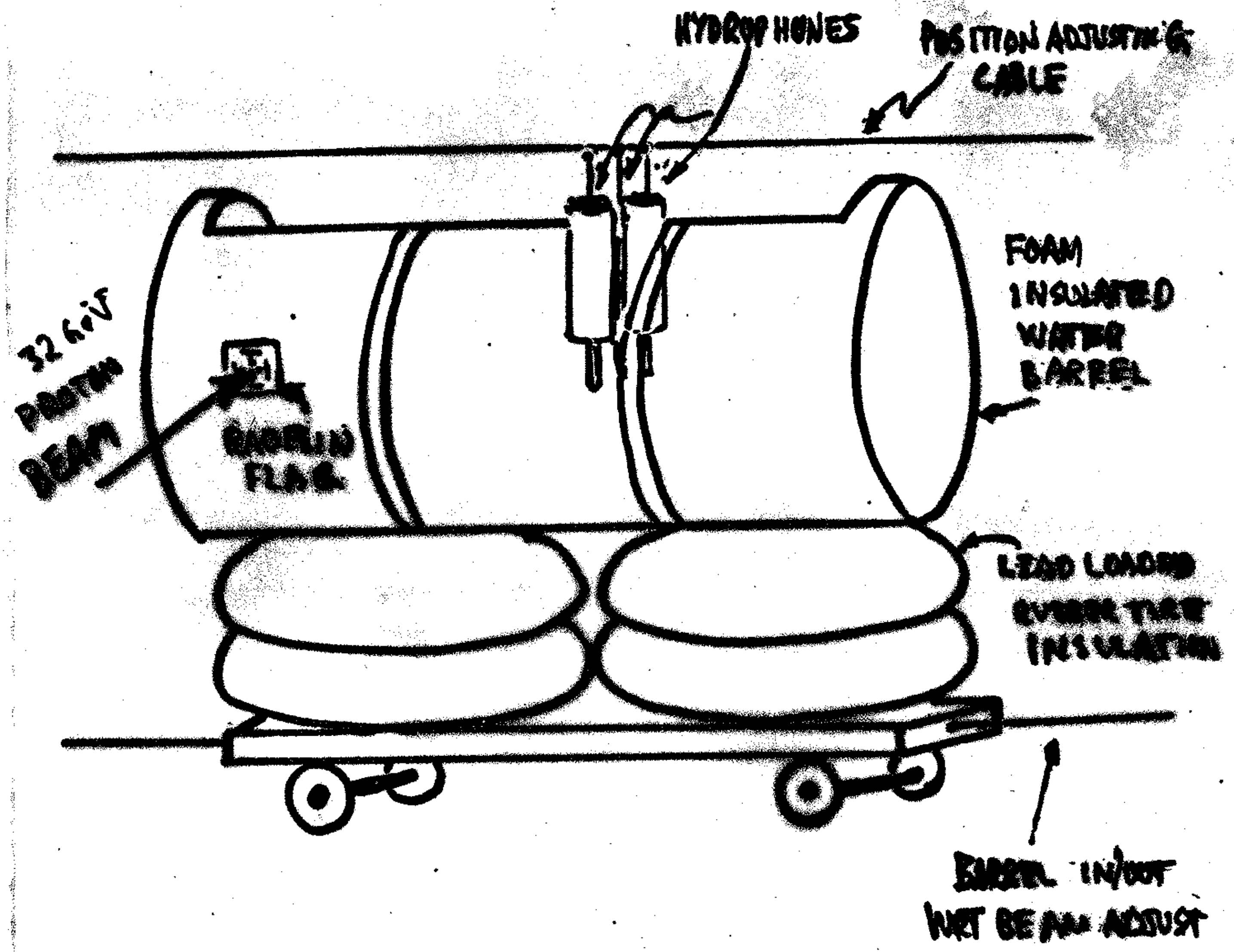
4ma, 100μsec spill

photo 100 pulses – same trace w Reflections ↓ from bottom



4 ma, 100μsec spill

BROOKHAVEN AGS SETUP



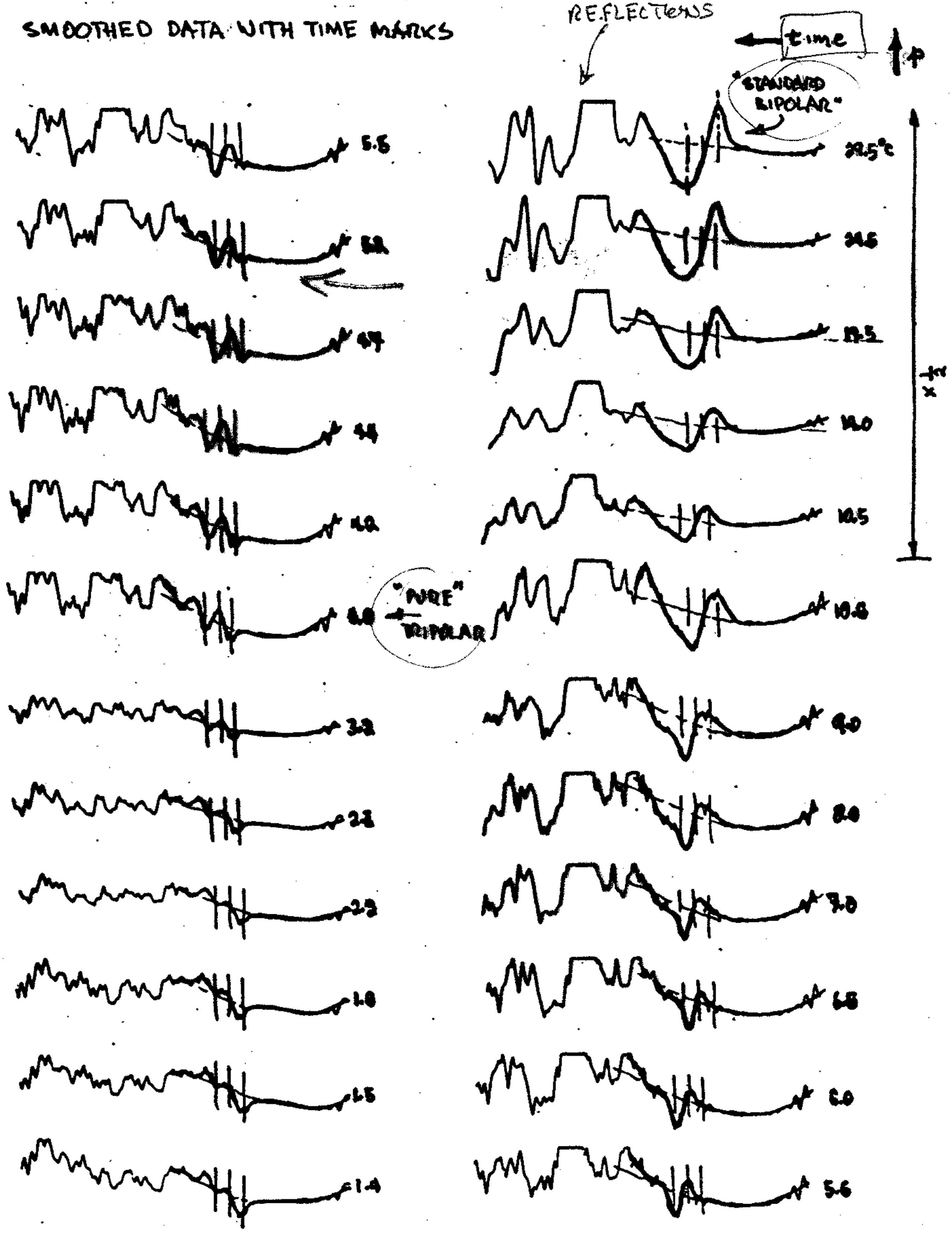
FRONT VIEW

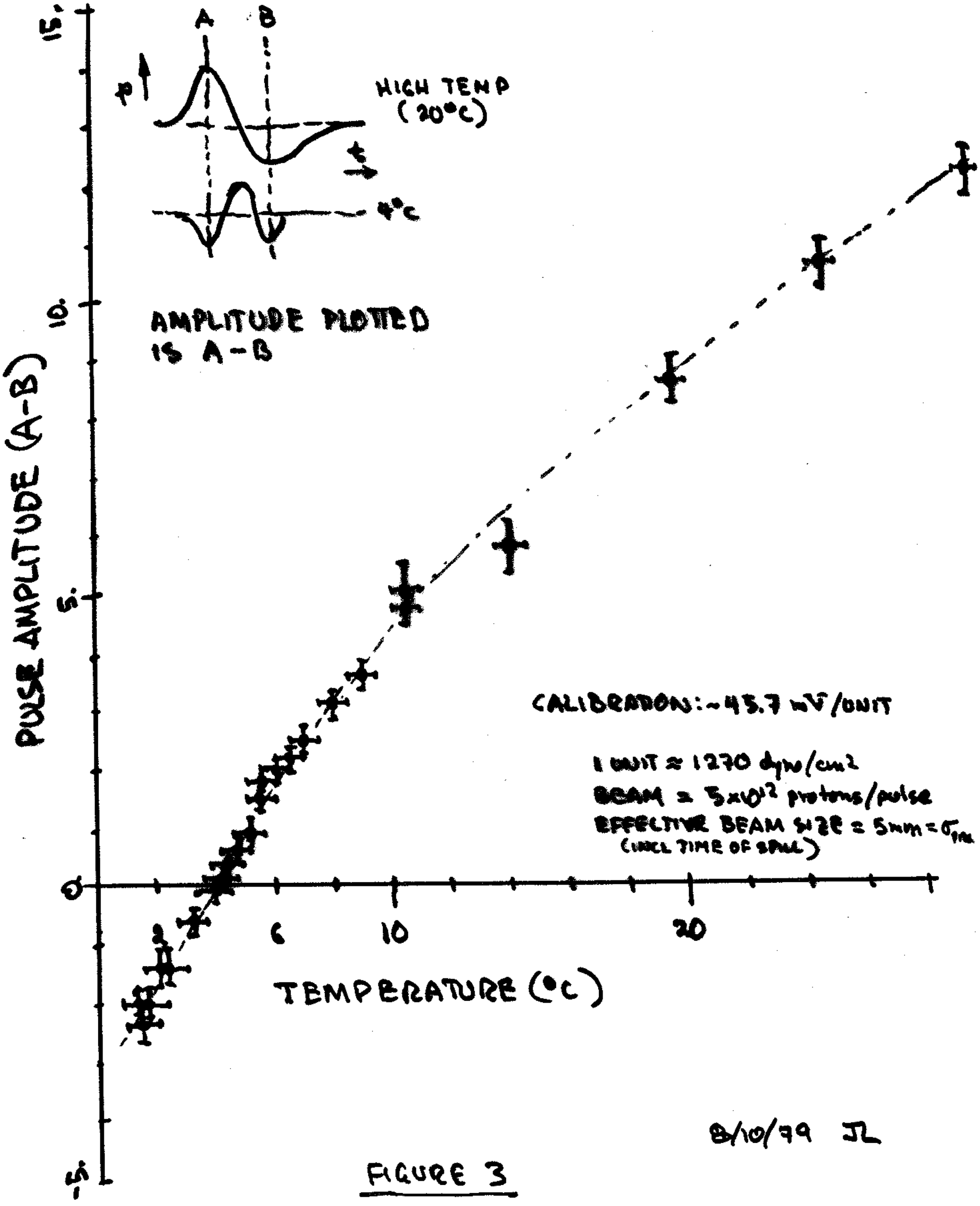
RECORD SIGNALS ON SCOPES & MAG TAPE

32GeV FAST EXTRACTED BEAM TEST APPARATUS

to naked ear, sound extremely loud,
high gain hydrophones
[illegible]

SMOOTHED DATA WITH TIME MARKS





CALIBRATION: ~45.7 mV/UNIT

1 UNIT ≈ 1270 dyn/cm²
BEAM = 5×10^{12} protons/pulse
EFFECTIVE BEAM SIZE = 5mm = σ_{rms}
(INCL TIME OF SPILL)

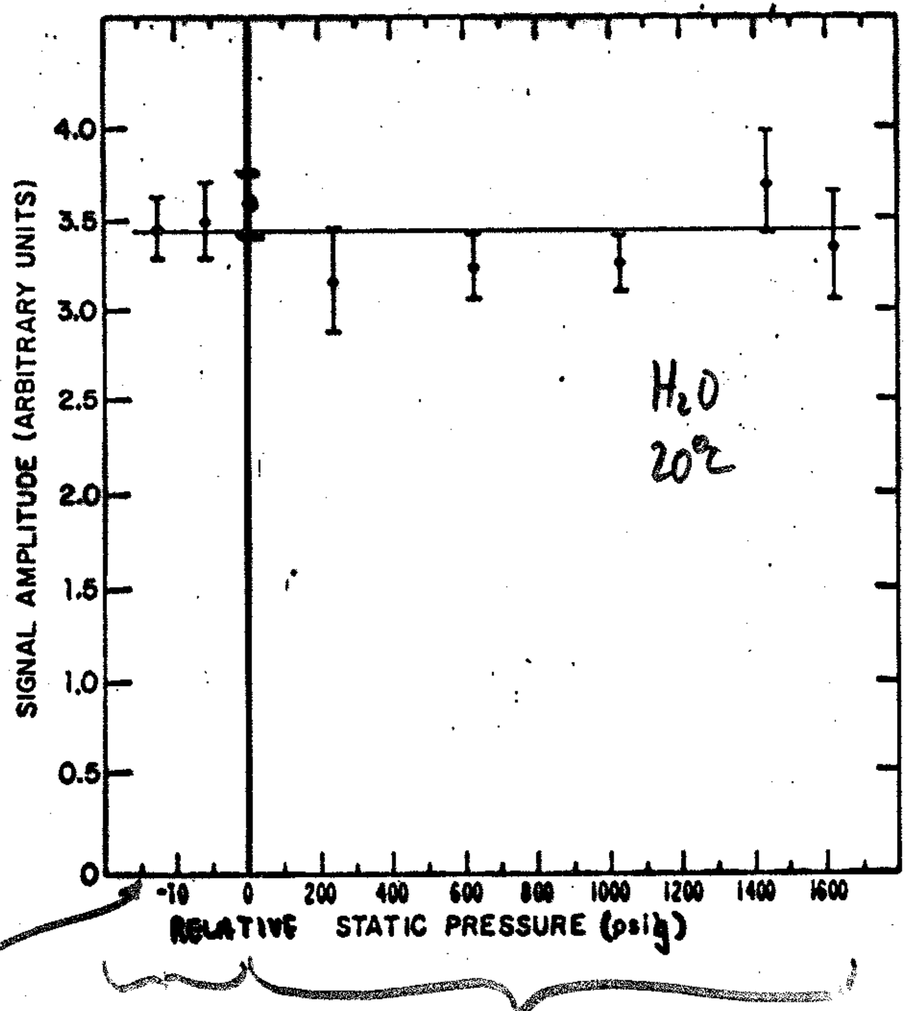
8/10/79 JL

FIGURE 3

HARVARD TESTS

NO AMBIENT PRESSURE DEPENDANCE

NO MICROBUBBLE SOUND EVIDENT

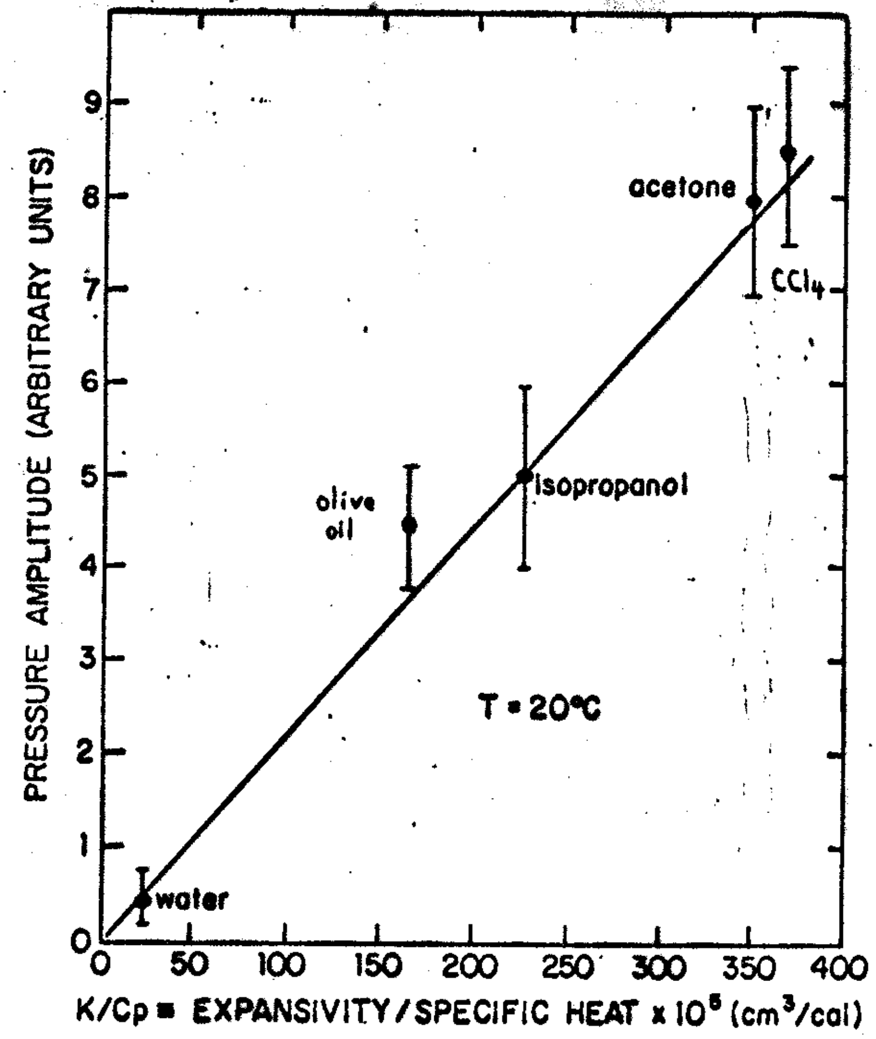


H_2O Vapor Pressure at 20°C

120 Atmospheres

HARVARD TESTS

$\frac{\beta}{C_p} = \frac{\text{EXPANSION}}{\text{UNIT HEAT}}$ DEPENDANCE



FIRST ROUND ACOUSTIC TESTS
CONCLUSIONS

- ✓ ABSOLUTE PRESSURE AMPLITUDE: OK TO WITHIN A FACTOR OF TWO

-

VARIABLE	VARIATION OF PULSE EXPECTED	ACCURACY
DISTANCE OF OBSERVATION	$\propto 1/R$ (THESE EXPTS)	~10%
ENERGY DEPOSITION	$\propto E$	OVER ×10^7 IN E
FREQUENCY CONTENT	$\propto \omega,\ \omega \ll \omega_0$	NOT INCONSISTENT
TEMPERATURE	$\propto \frac{\beta(T)}{C_p}$	~10%
VARIOUS MATERIALS	$\propto \beta/C_p$	~10%
AMBIENT PRESSURE	$\not\propto P$	< 10% OVER 100 ATM
SMALL SALT CONCENTRATION	SLOW CHANGE	OK
"SIZE" OF DEPOSITION REGION	$\tau \propto d$	OK
z/β OF PARTICLE	$\propto (z/\beta)^2$	UNTESTED

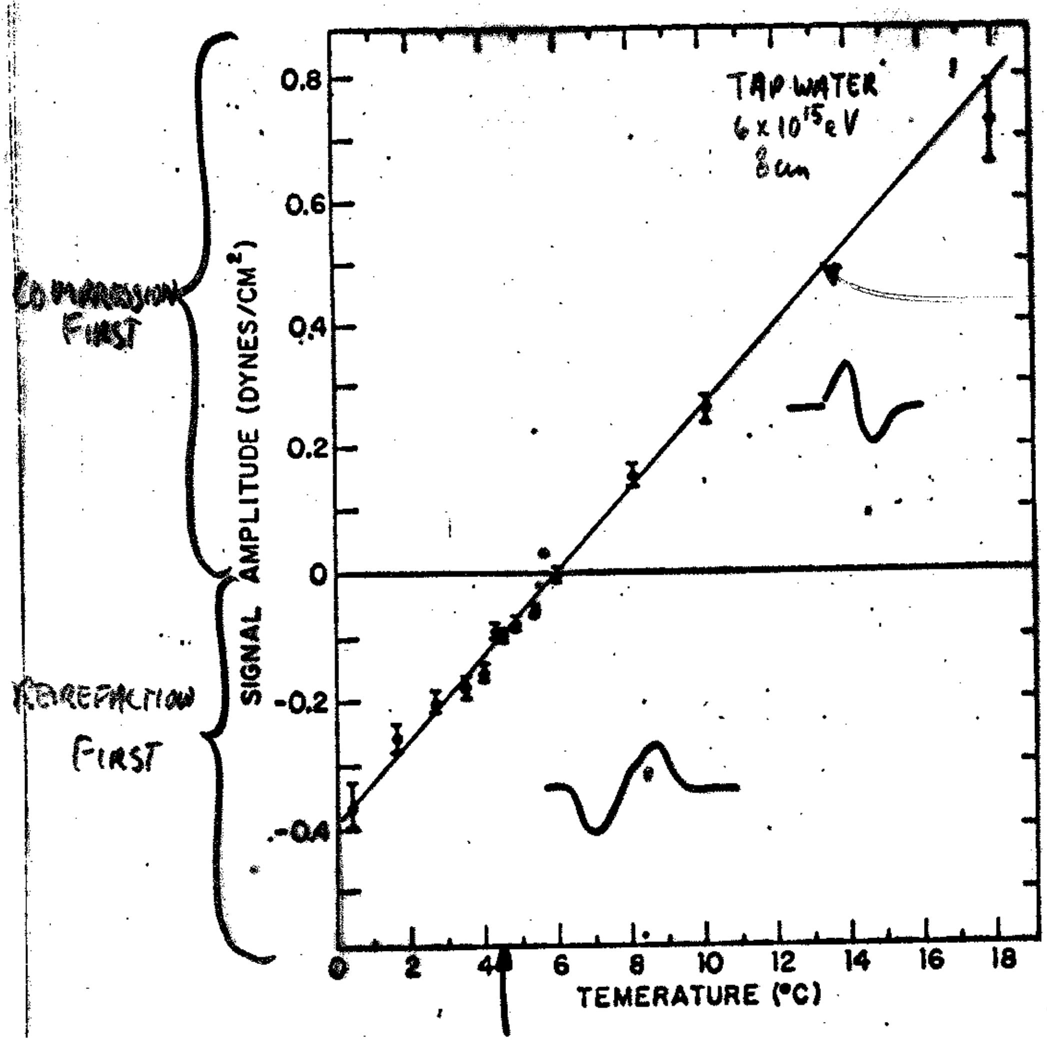
✓ I SIMPLE THERMOACOUSTIC MODEL GIVES WHOLLY ADEQUATE FIRST ORDER DESCRIPTION OF ACOUSTIC RADIATION

✓ II WE SEE NO EVIDENCE FOR ANY MICROBUBBLE PRODUCTION IN WATER ANYWHERE NEAR STP CONDITIONS

$\hookrightarrow$ LAr + CCl_4 + Hg
WITH Fe NUCL

HARVARD TESTS

TEMPERATURE DEP.



$\frac{K}{C_p} \propto T$

in this region of

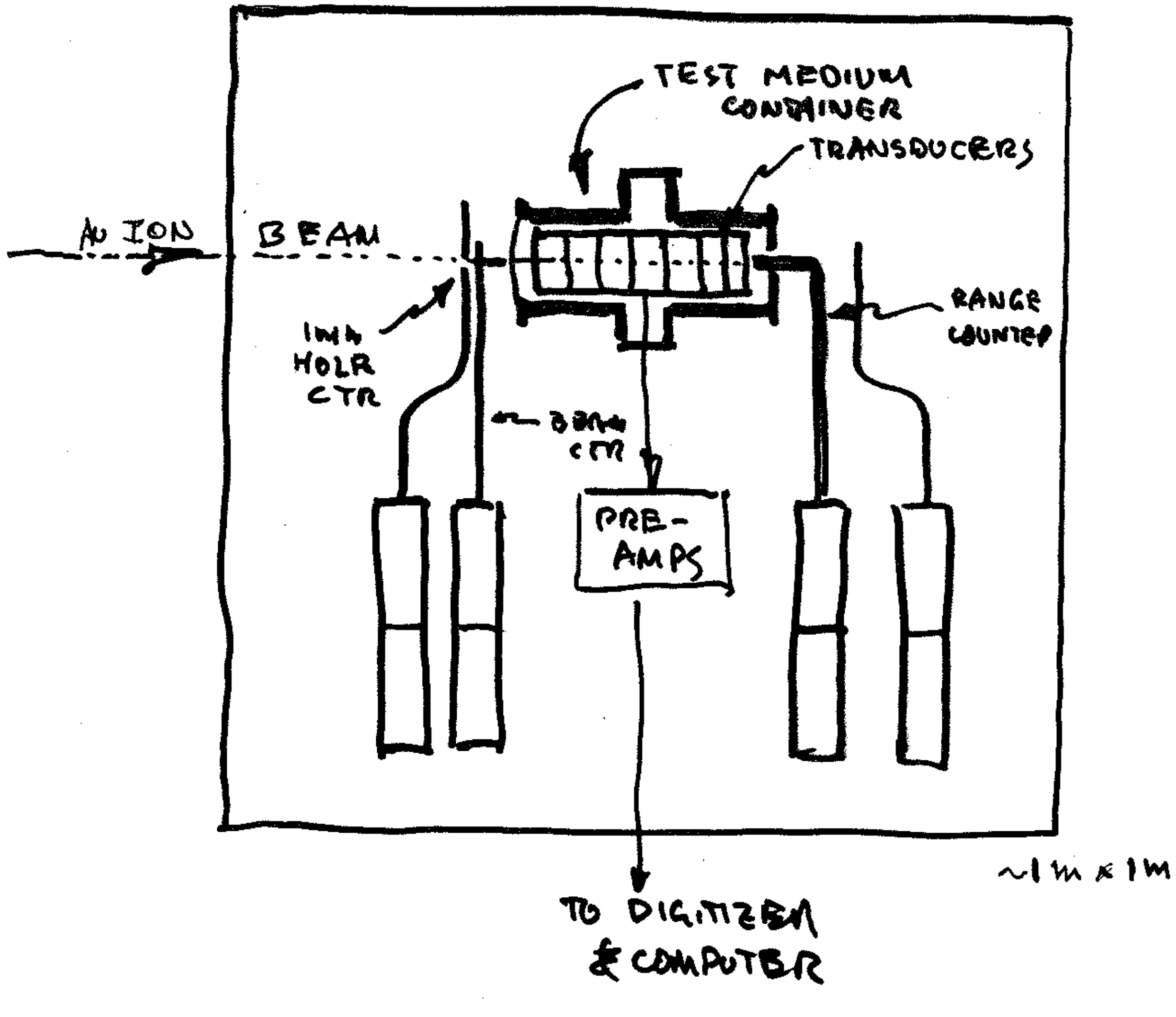
4.3°C

(3-4σ)

ZERO CROSSING AT ~6°C NOT UNDERSTOOD

HEAVY ION DETECTION AT LBL (1979)

ONE OF 3 DETECTOR LAYOUTS



NO SIGNAL DETECTED ABOVE (HIGH) NOISE

⇒ NO SIGNIFICANT NEW MECHANISM AT VERY HIGH dE/dx

CAN DEEP OCEAN ARRAYS DETECT EAS?

PROBABLY YES FOR EeV SHOWERS

$$S/N \approx 4\times10^{-4} \times \frac{E}{10^{17}\,\mathrm{eV}} \times N_{HYD}$$

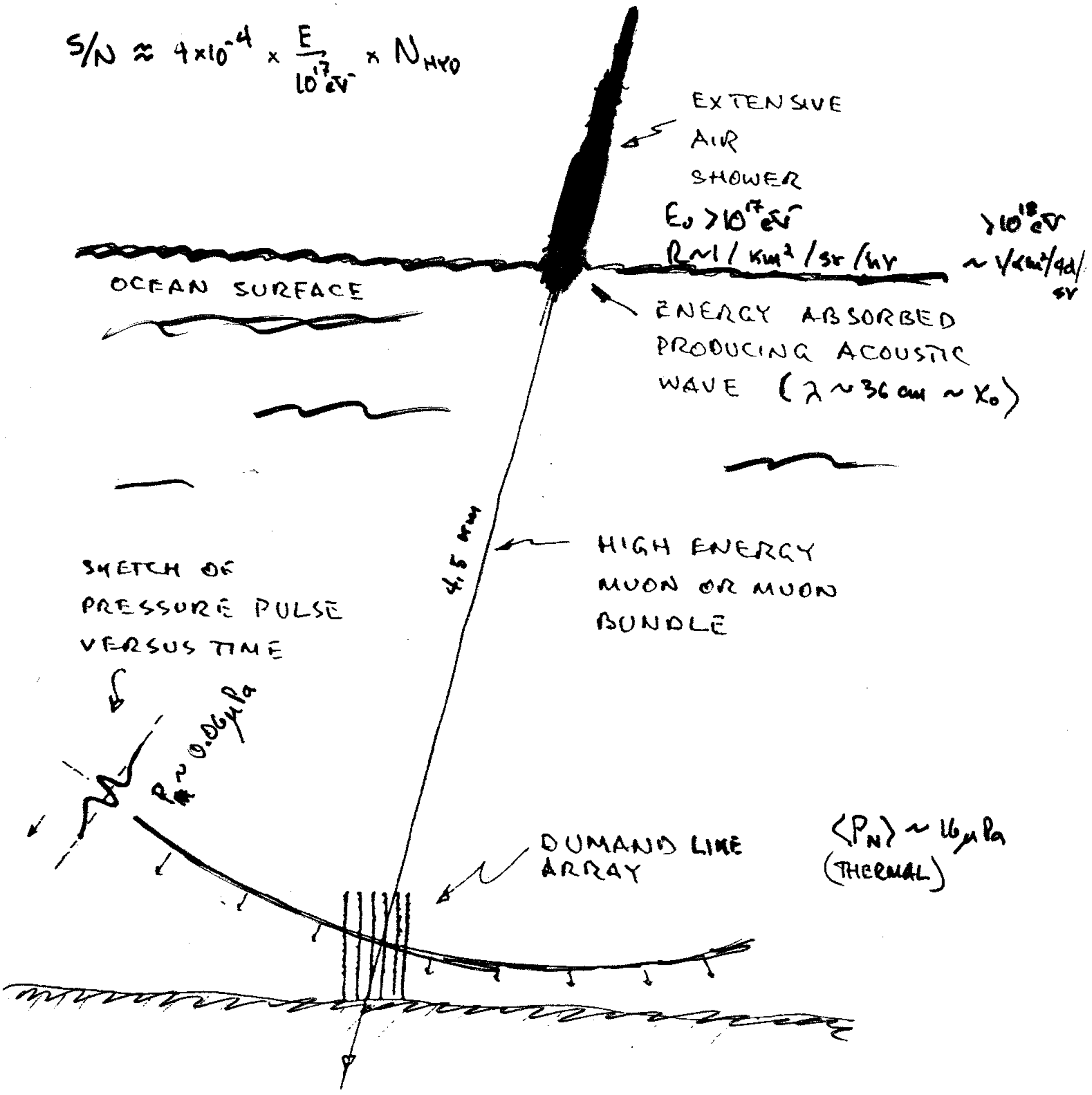


Figure 1

:matic illustrating the possible use of acoustic waves to measure EAS 'gy deposition at the ocean surface above DUMAND.

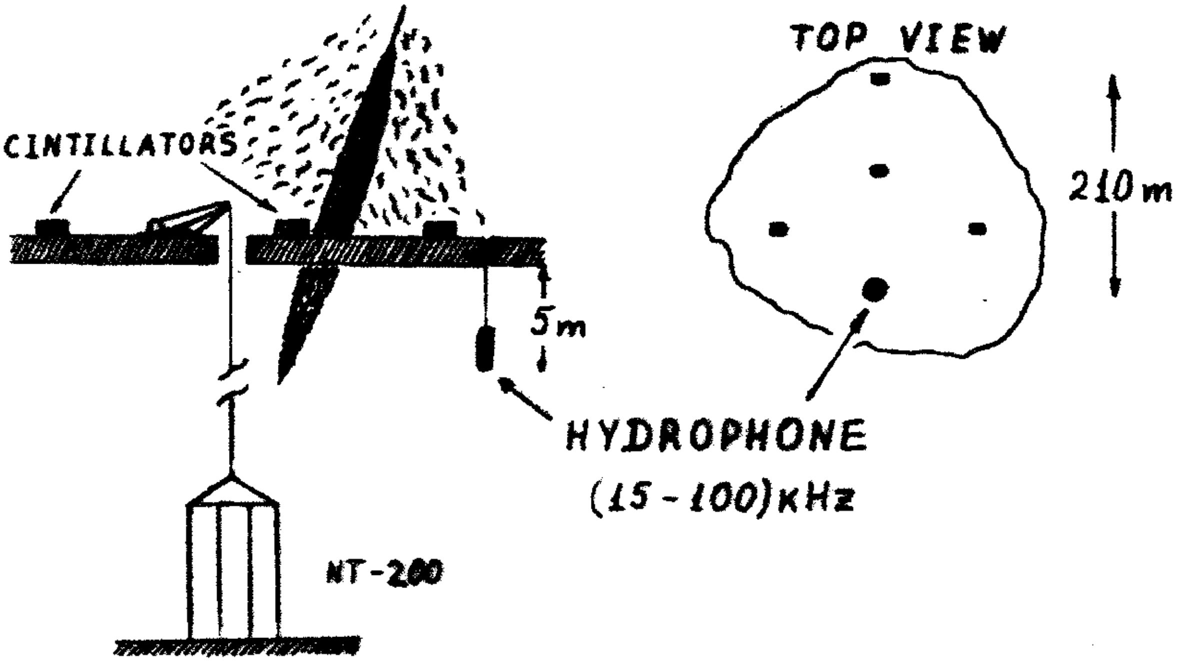
JGL 6/86
US-JAPAN SEMINAR

NEW RESULTS! 2000

BAIKAL GROUP

FIRST OBSERVATION
2000y

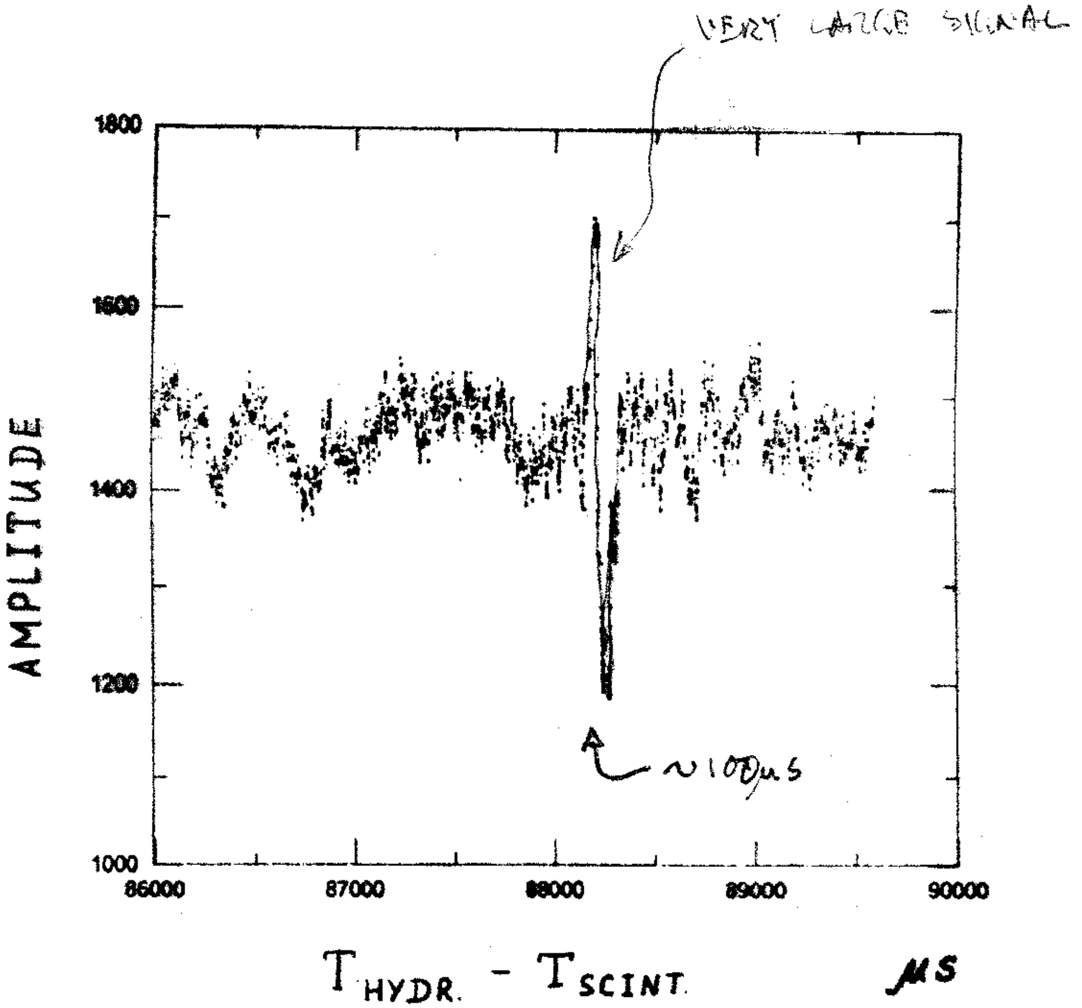
EAS ARRAY + HYDROPHONE



EAS TRIGGER - 4-FOLD COINCEDENCE

RATE OF EAS TRIGGER	3 $hour^{-1}$
ENERGY THRESHOLD	$\sim 10^{16}$ eV
RATE OF EAS TRIGGER + HYDROPHONE	1 $hour^{-1}$

G. DOMOGATSKI @ V 2000



SAMPLE OF REGISTRATED SIGNAL

RATE ~OK FOR 10^{17} eV
BUT SIGNAL SEEMS LARGE

SIZE ~100μs × 1.5 mm/μs = 15 cm ⌀
↑
SHOWER CORE

[illegible]
[illegible]

CONCLUSION

- MANY YEARS SINCE EXP'TS
  - NEW TECHNOLOGY
  - NEW SCIENTIFIC MOTIVATION GZK ν's ?
  - NEW CALCULATIONS
  - NEW PEOPLE !

- SHOULD LOOK AT PROSPECTS FOR
  - LAKE EAS
  - DEEP OCEAN W/ WATER CHERENKOV ν TELES.
  - SALT DOMES W/ RADIO ?
  - ? MOON

⋮