NLC MAC, Fermilab, June 1, 2000

Vladimir Shiltsev

(FNAL/BD)

What can we learn from ground motion measurements at FNAL?

contributors :

FNAL — Shiltsev V.
Lach J.

Novosibirsk — Parkhomchuk V.
Chupyra A.
Kondaurov M.
Singatulin S.
Baklakov B.
Erokhin A.

ANL — Friedsam H.

welcome to :

http://www-ap.fnal.gov/~shiltsev/

What kinds of ground motion are dangerous for accelerators?

Parallel displacement - OK

tides only
$\lambda = 20{,}000$ km
$T = \frac{1}{2}$ day

Tilt (as a whole) - OK

microseismic waves
$\lambda \sim 20$ km
$T = 7$ sec

tides $\lambda = 20000$ km $T =$

Short wavelength - danger!

"man-made"
in $f \sim 5 - 60$ Hz

Uncorrelated fractures - danger!

Natural ground motion

P. Tenenbaum

V. Nosochkov, 02-10-98

SLAC

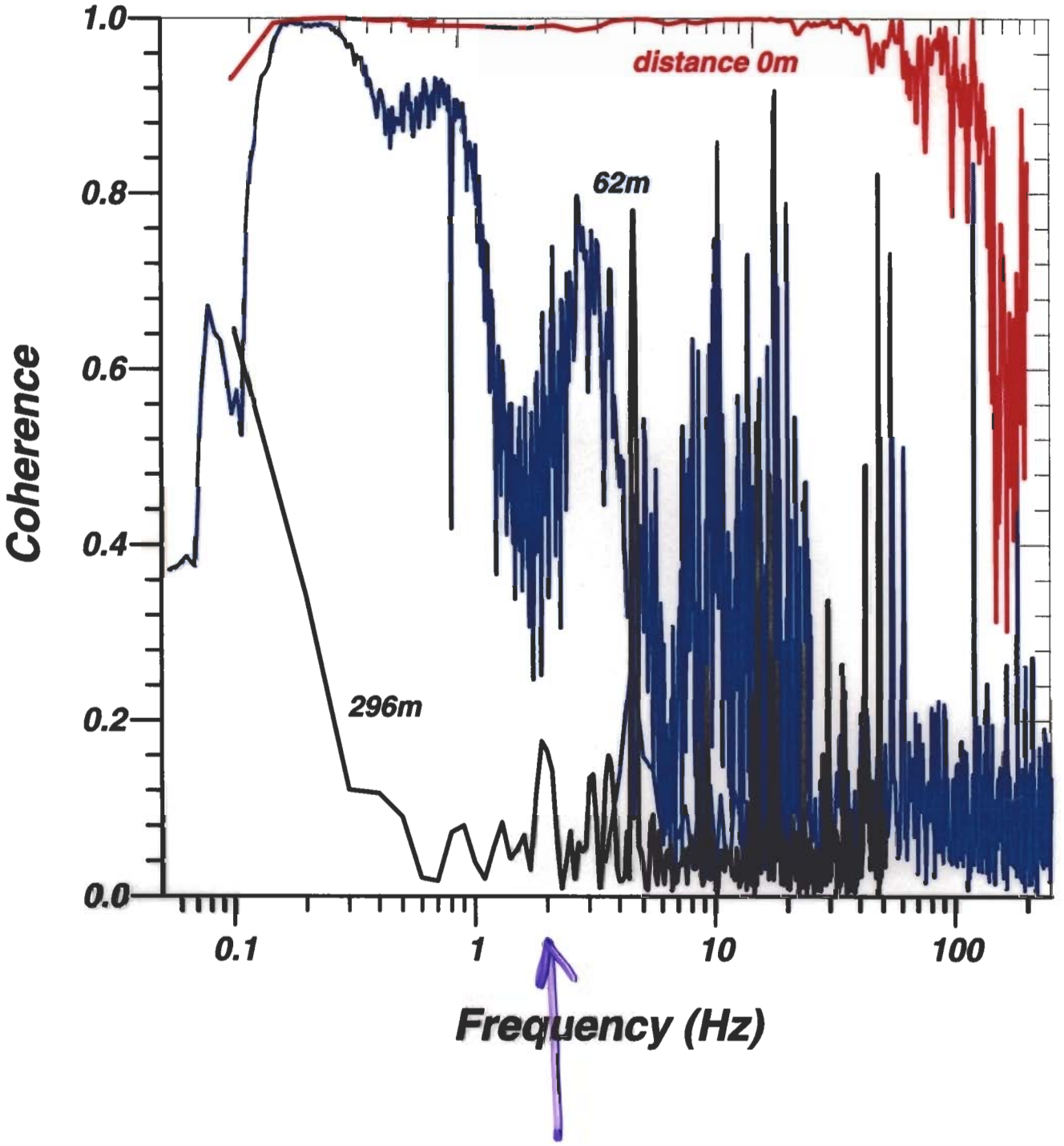
Tolerance comparison: NLC

Input parameters:

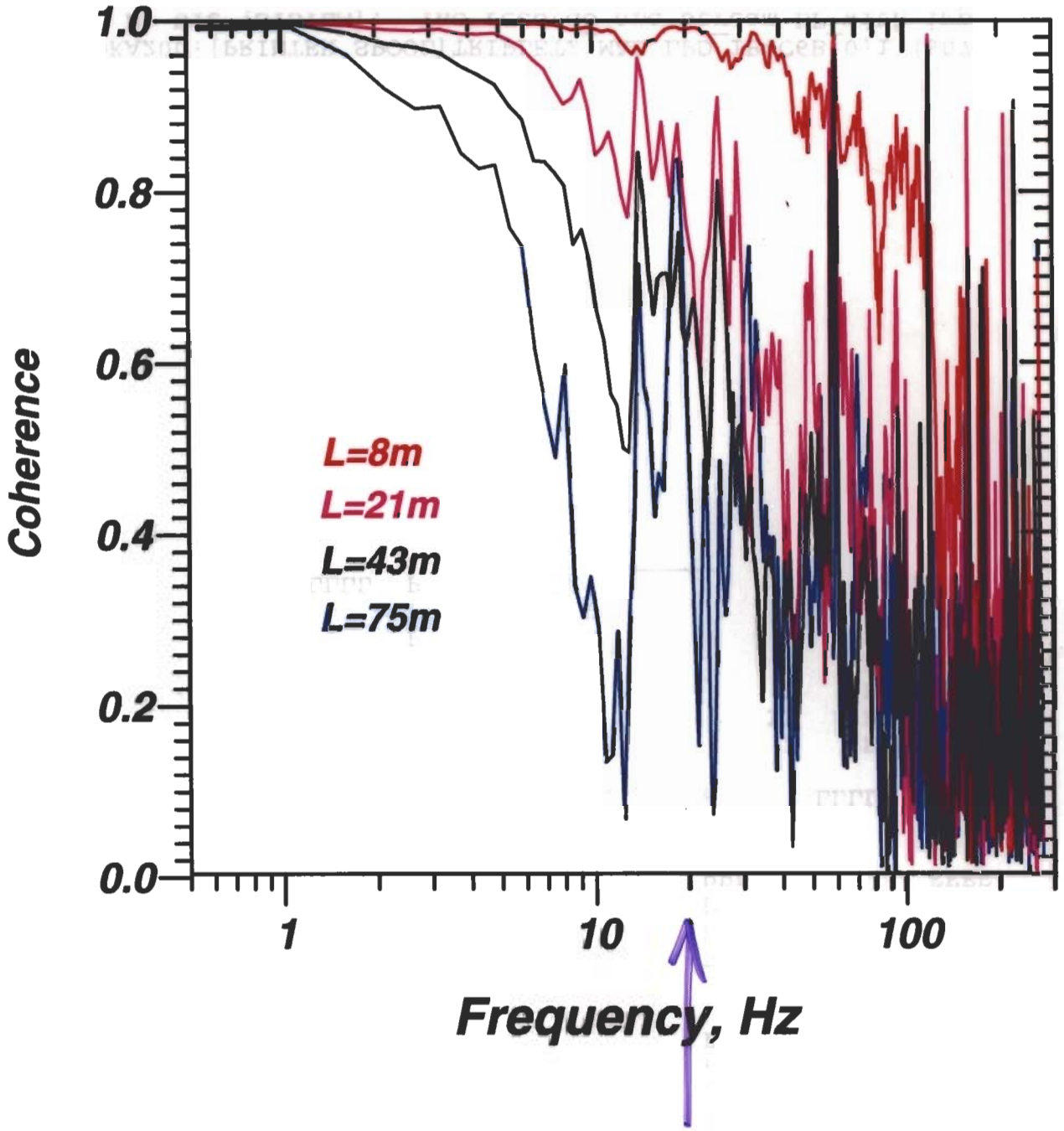
Number of particles per bunch: $N = 1.1 \cdot 10^{10}$
Bunch length (rms): $\sigma_z = 150\ \mu m$
Wakefield value : $W_\perp = 9.95 \cdot 10^{19}\ V/c/m^3$

		2-RF FODO	3-RF FODO	3 - w doublet + FODO (1)	3-RF doublet + FODO (2)
Total length (m)		9715.78	9756.95	9780.27	9780.27
Number of quads		740	690	748	748
Length of quads (m)		378.90	430.92	445.55	445.55
Max. quad grad. (kG/m)		1746.10	1686.47	1865.62	1911.14
Total betatron phase (2π)	x	92.26	86.17	85.32	85.35
	y	92.26	86.18	85.27	85.26
Quad. displacement tolerance for 25% emit. dilution (μm)	x	102.2	132.3	65.1	65.2
	y	10.2	13.2	6.28	6.27
Quad jitter tolerance for 25% beam jitter (μm)	x	0.0706	0.0712	0.0672	0.0672
	y	0.0071	0.007 1	0.0067	0.0067
Acc. struct. displac. tolerance for 25% emit. dilution. X-band. (μm)	x	45.3	43.1	43.4	43.4
	y	4.53	4.31	4.34	4.34

FNAL site, on surface
1997 data, Phys. Rev ST. AB



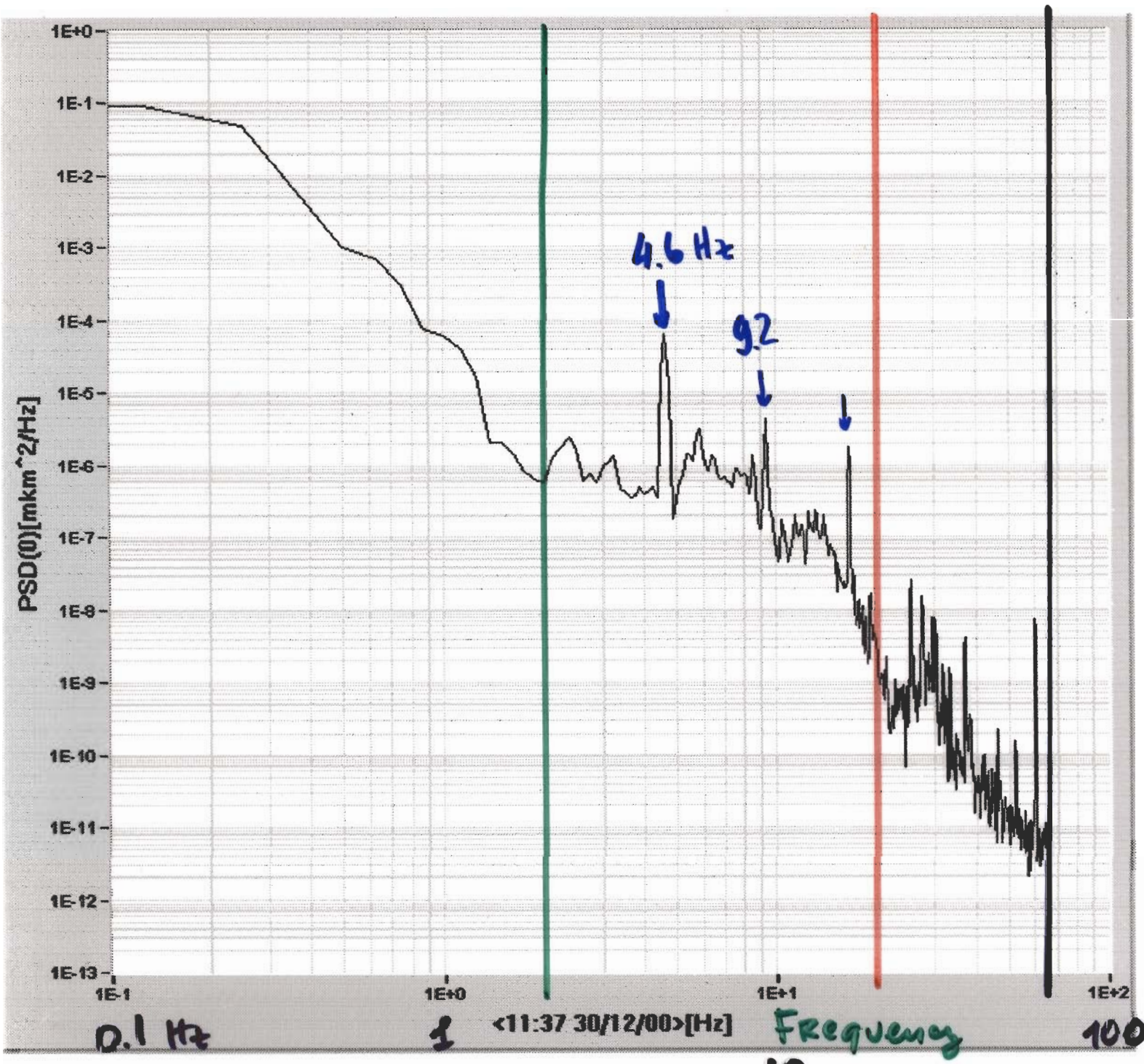
Deep ILL dolomite tunnel
1997 data, Phys. Rev ST·AB

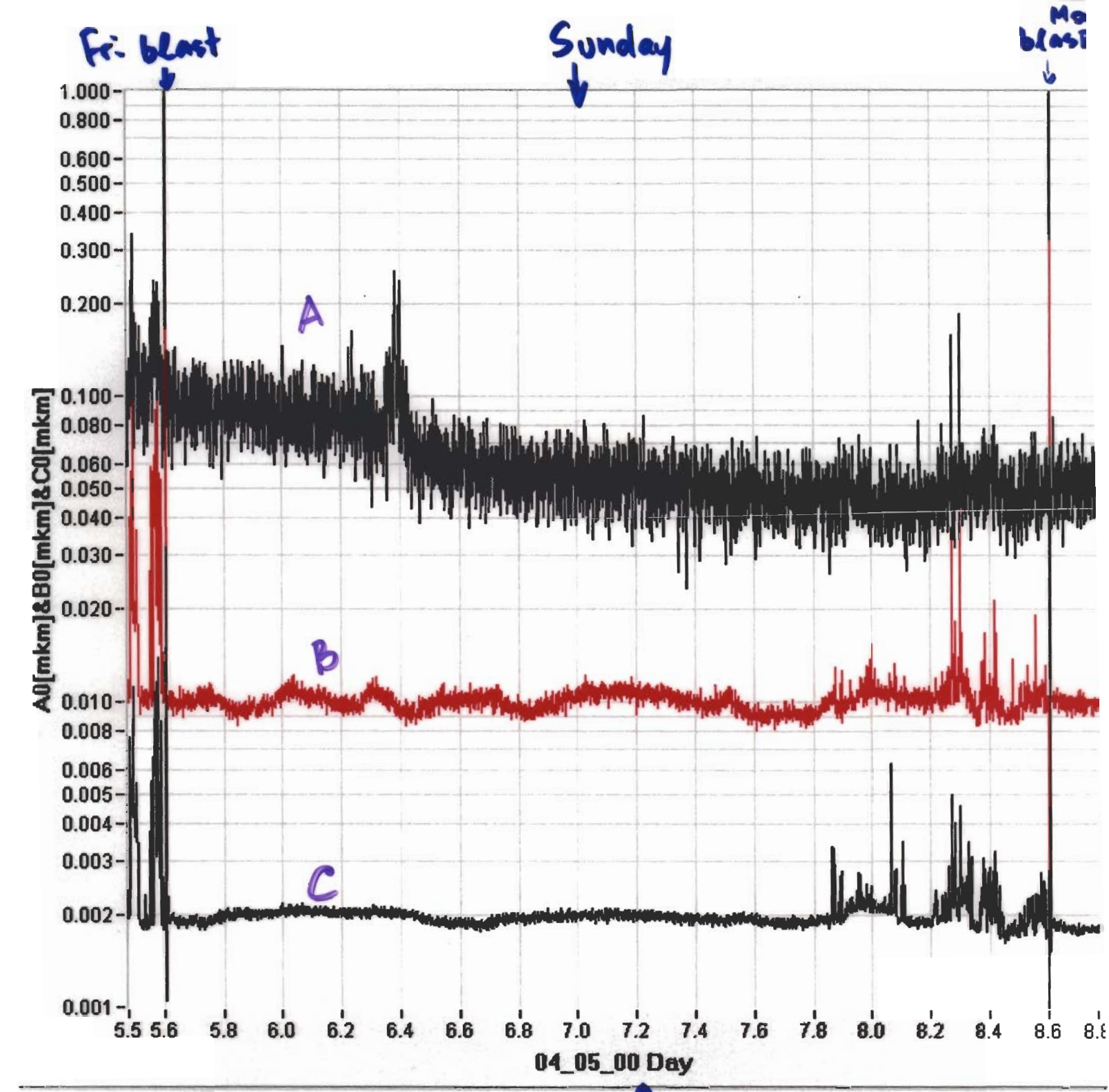


$$A = \left[\int_0^{2\,Hz} PSD \cdot df\right]^{1/2}$$

$$B = \left[\int_2^{20\,Hz} PSD \cdot df\right]^{1/2}$$

$$C = \left[\int_{20}^{64} PSD\,df\right]^{1/2}$$





↑ Aurora mine

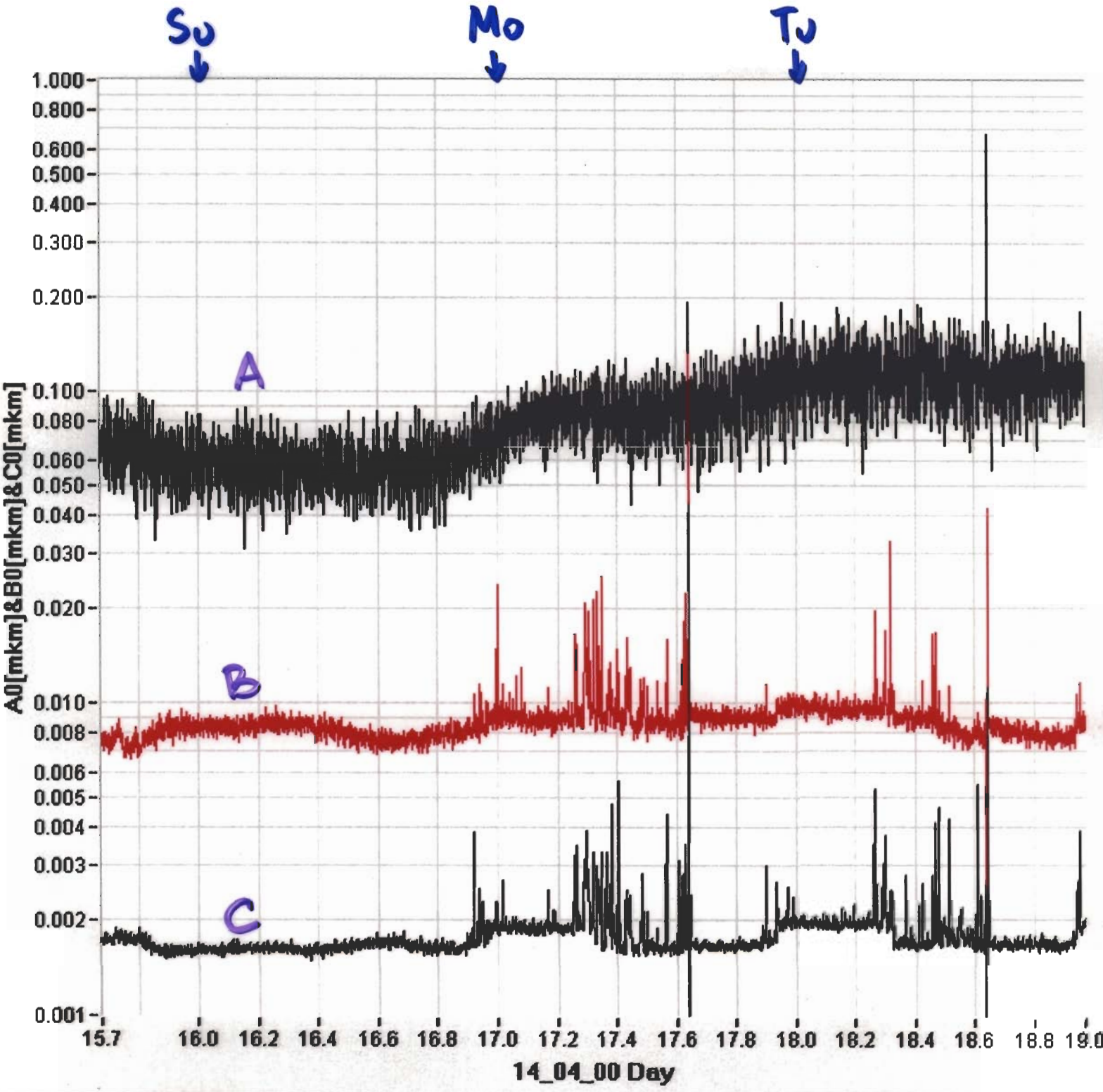
vertical vibration ampl.

A = rms in 0-2 Hz

B = rms in 2-20 Hz

C = rms in 20-64 Hz ← ≡ "uncorrelated" for NLC

Aurora mine data



Amplitude of vertical ground vibrations:

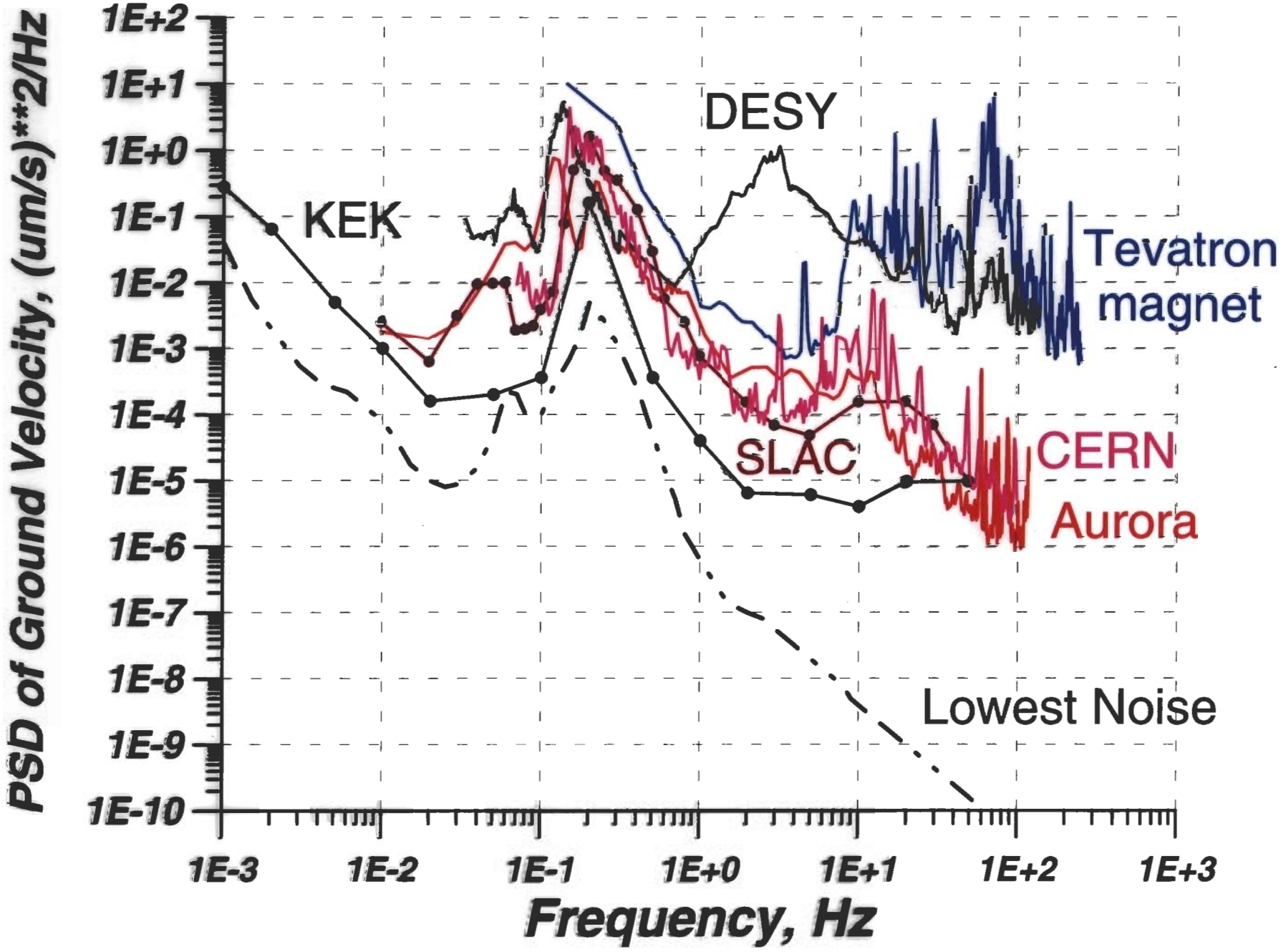
A = rms in 0.1 - 2 Hz

B = rms in 2 - 20 Hz

C = rms in 20 - 64 Hz

1997, Phys. Rev. ST-AB

Ground Motion Spectra at FNAL and Other Labs



1997 data, Phys. Rev. STA (1998)

Comparison of Experimental Data:

Tev-Quad(F11), vert
s2908052, s2908035, s0209049

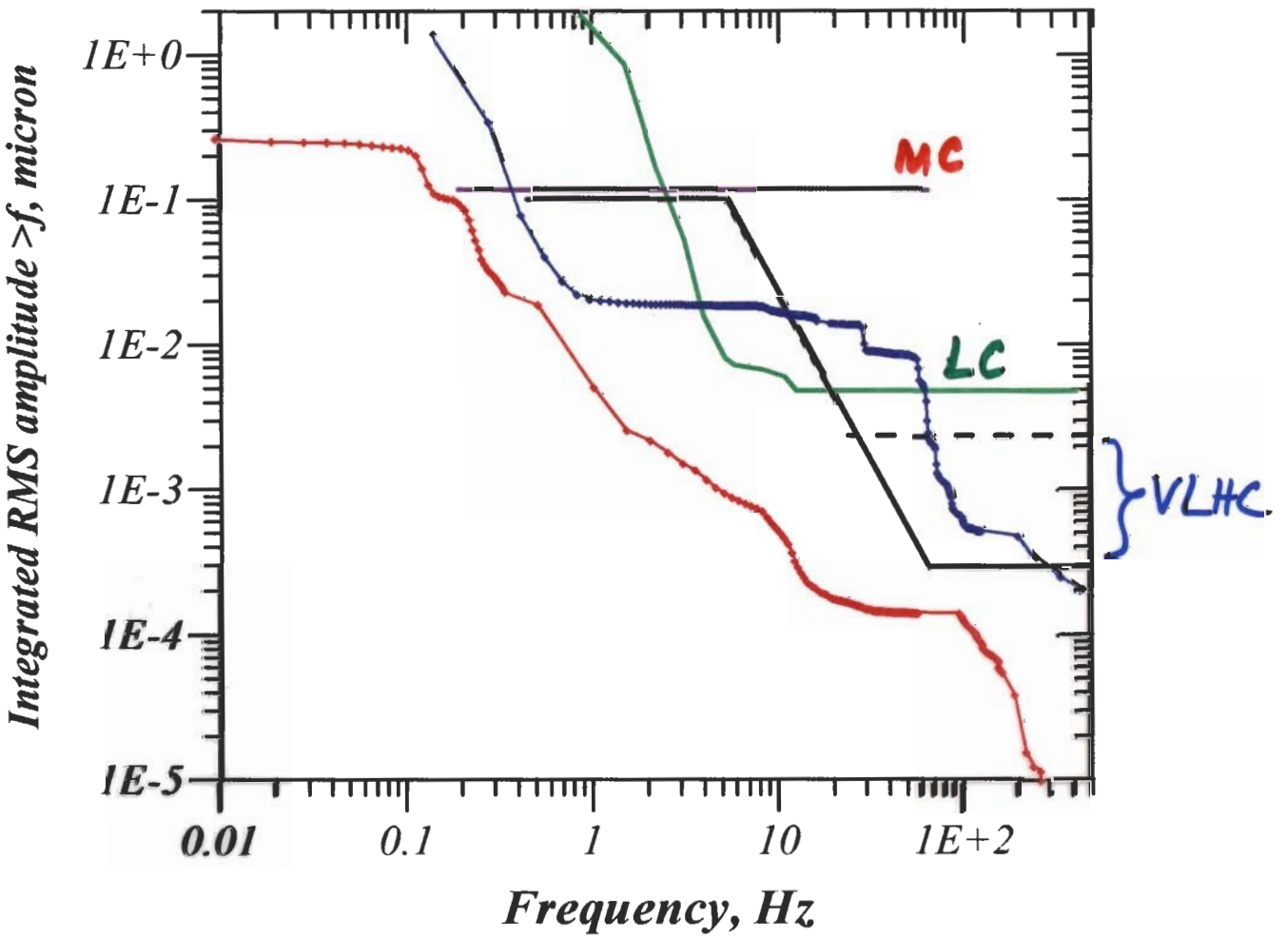
Conco mine (Aurora) 4 Oct. 97
s0410012, s0410018

with Future Collider Tolerances:

Muon Collider : 0.1 sigma off-center collisions (IR only)

X-band Linear Collider: 1.5% Luminosity Drop

VLHC: emittance growth time of 5 hrs (dash - with FB)
+ 0.1 sigma beams oscillations



Summary on high-frequency ground vibrations:

a) the "NLC-relevant" uncorrelated ground vibrations (dozen(s) meter distance between obseravtion points, f>2 Hz) measured in the Fermilab PW6-7 tunnel vary from 3-5 nm during nights/weekends to 20-30 nm at daytime.

b) in deep dolomite tunnel (Aurora mine) the amplitude the "NLC-relevant" uncorrelated" ground motion is about 2 nm (excluding blasts).

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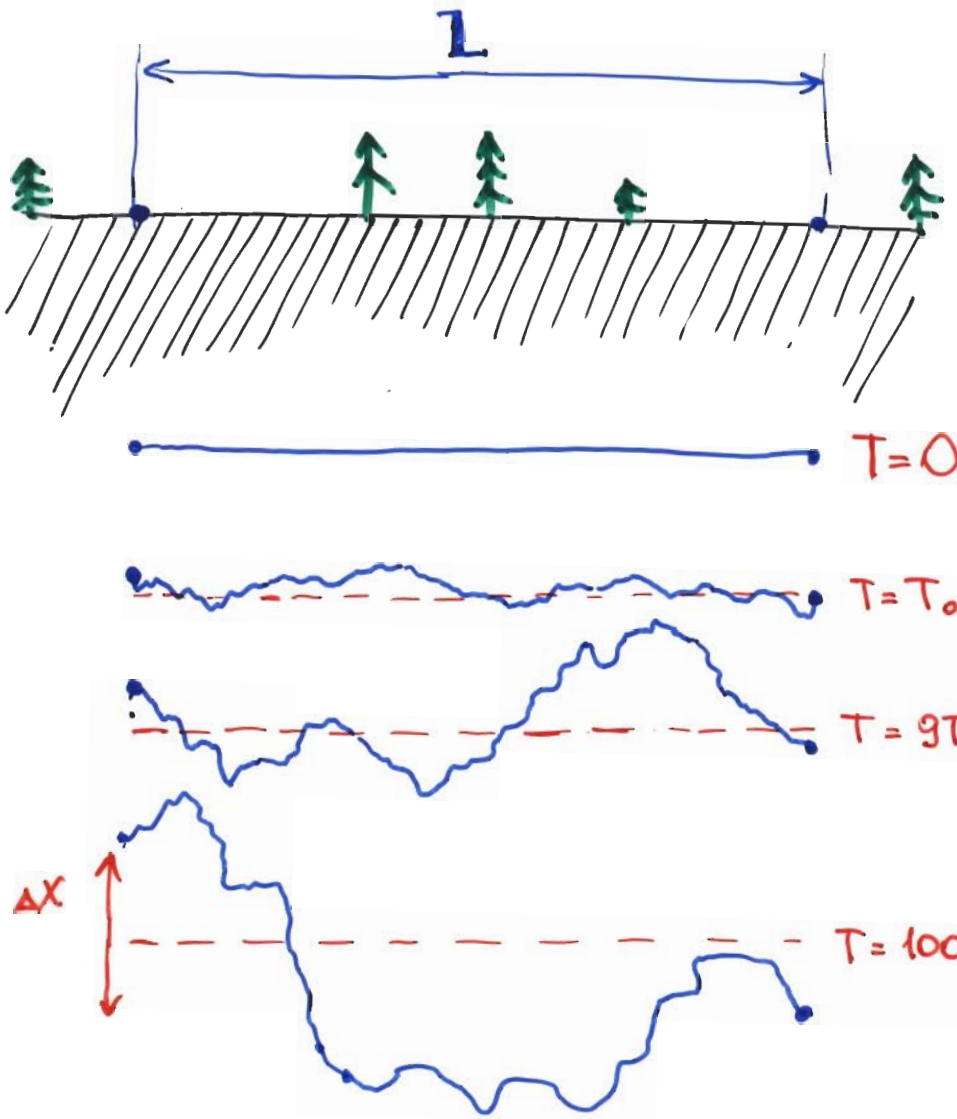
Space-Time Ground Diffusion - The ATL Law for Accelerators



BESIDES GROUND MOTION DUE TO:

1) TIDES
2) PRECIPITATION
3) T° VARIATIONS
4) WINDS
5) GROUND WATER
6) ETC/SETTLEMENTS

↓

DIFFUSION (RESIDUAL)

MEAN IN TIME+SPACE

TIME INTERVAL

$$\langle\langle \Delta X^2 \rangle\rangle = A \cdot T \cdot L$$ ← 1991

SPATIAL INTERVAL

relative displacement (H,V)

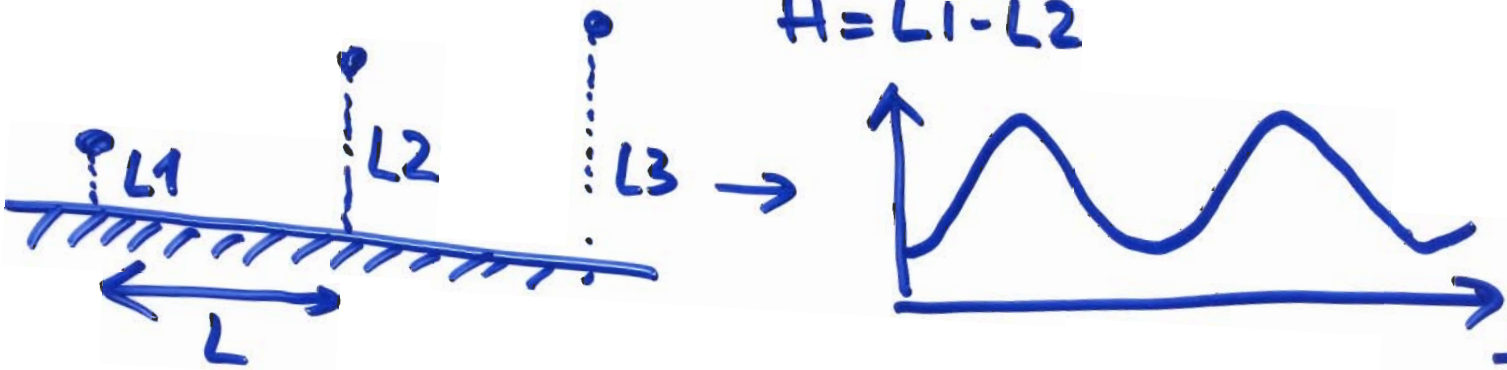
$\Delta X = X_2 - X_1$

DIFFUSIVE COEFFICIENT

$\sim 10^{-5 \pm 1} \frac{\mu m^2}{s \cdot m}$

Elevation Difference

$H = L1 - L2$

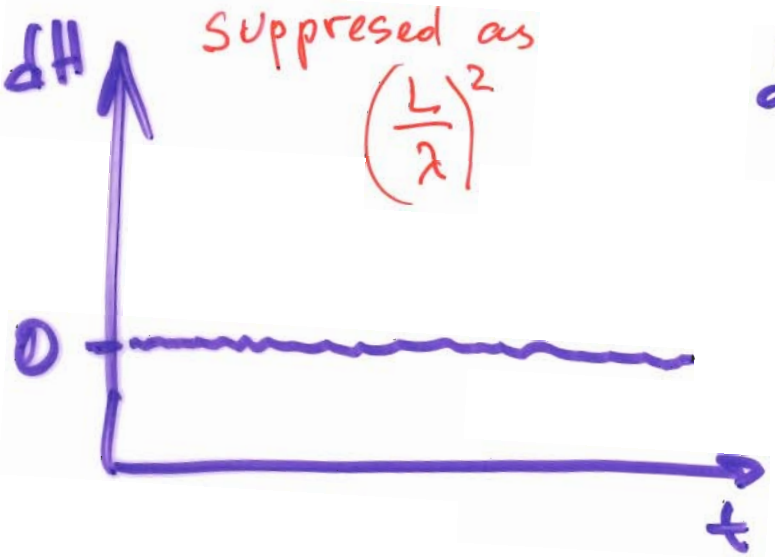


How to extract uncorrelated motion –
– component with short correlation length?

Calculate the second difference (fracture)

$$dH = (L1 - L2) - (L2 - L3) = L1 - 2 \cdot L2 + L3$$

long wavelength



uncorrelated

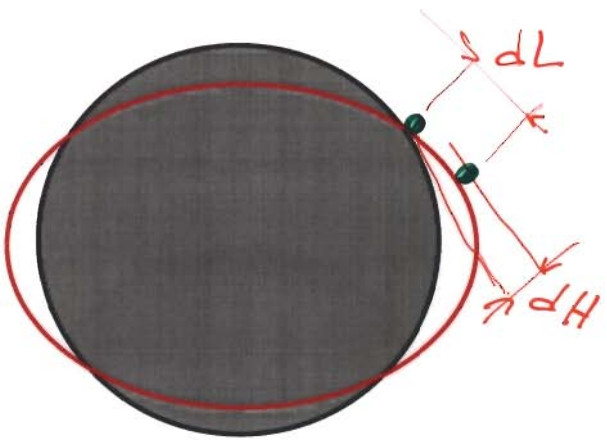
e.g. $\langle dH^2 \rangle = 2 \cdot A \cdot T \cdot L$

for "ATL-like" motion

Tides

Moon

Sun

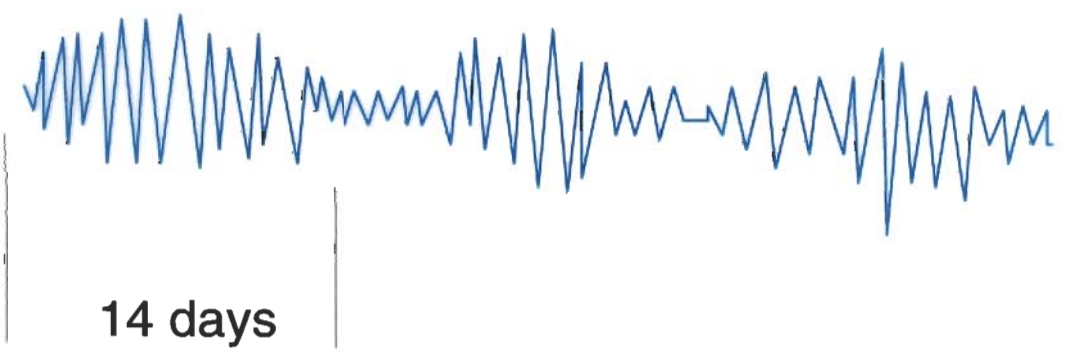


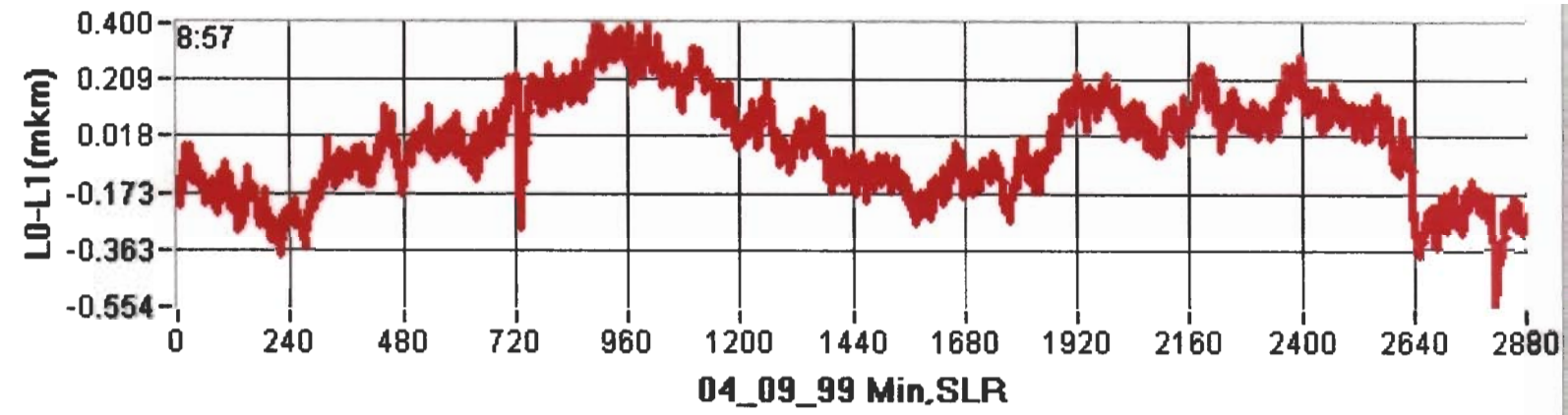
Earth

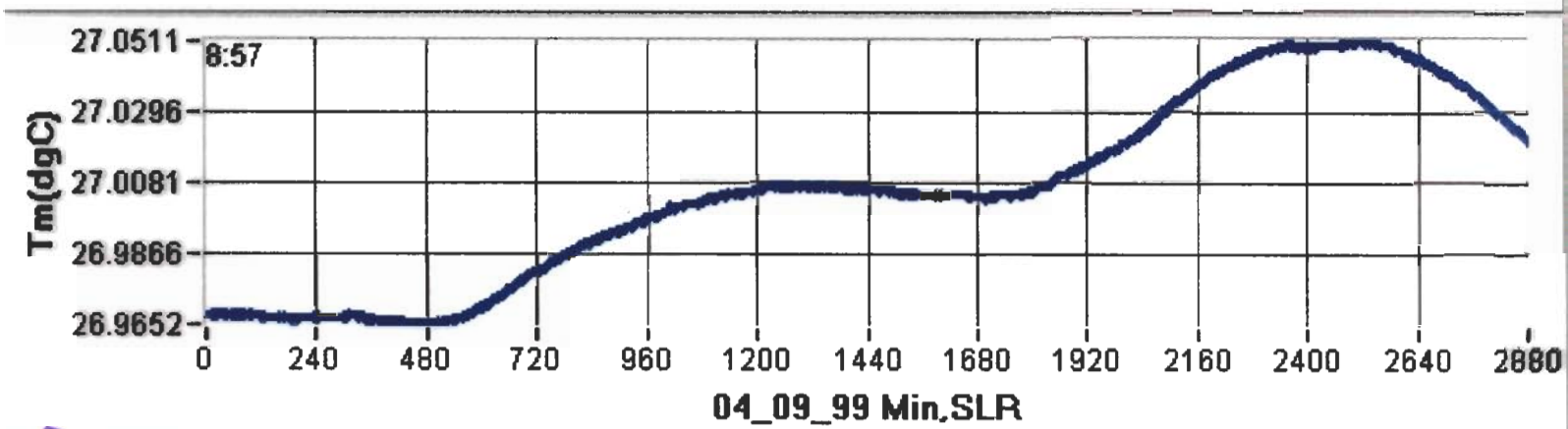
dH=A * Sin (2*3.14*dL/ Lambda) where
dH - peak-to-peak water level difference,
A - tide peak-to-peak amplitude, dL-
distance between probes, Lambda=20,000 km,

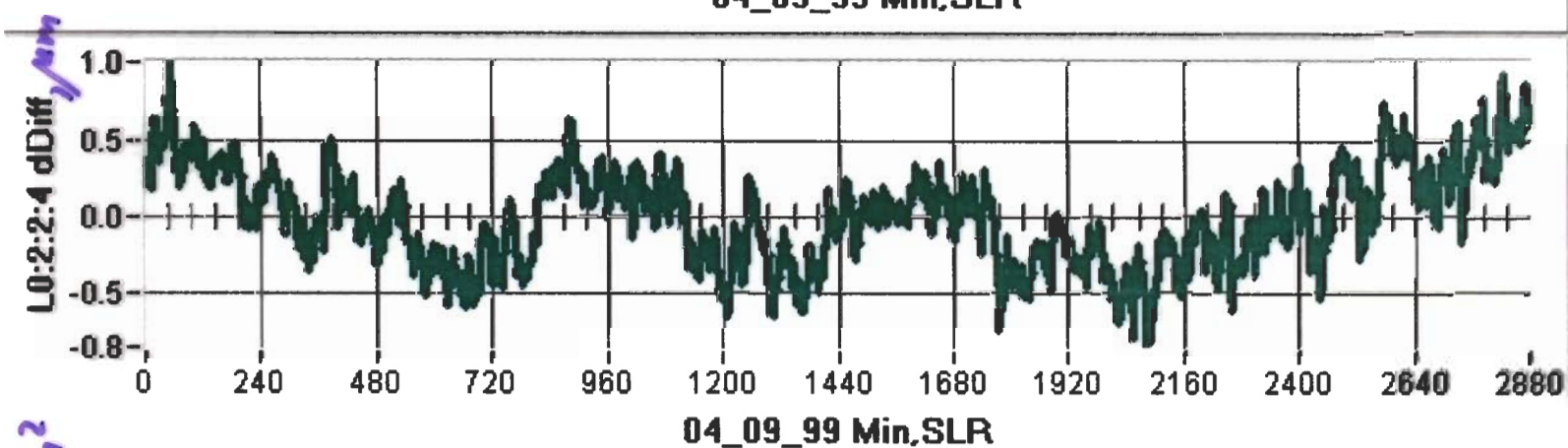
e.g., dH=12 microns, dL=120 meters, A=0.3 m

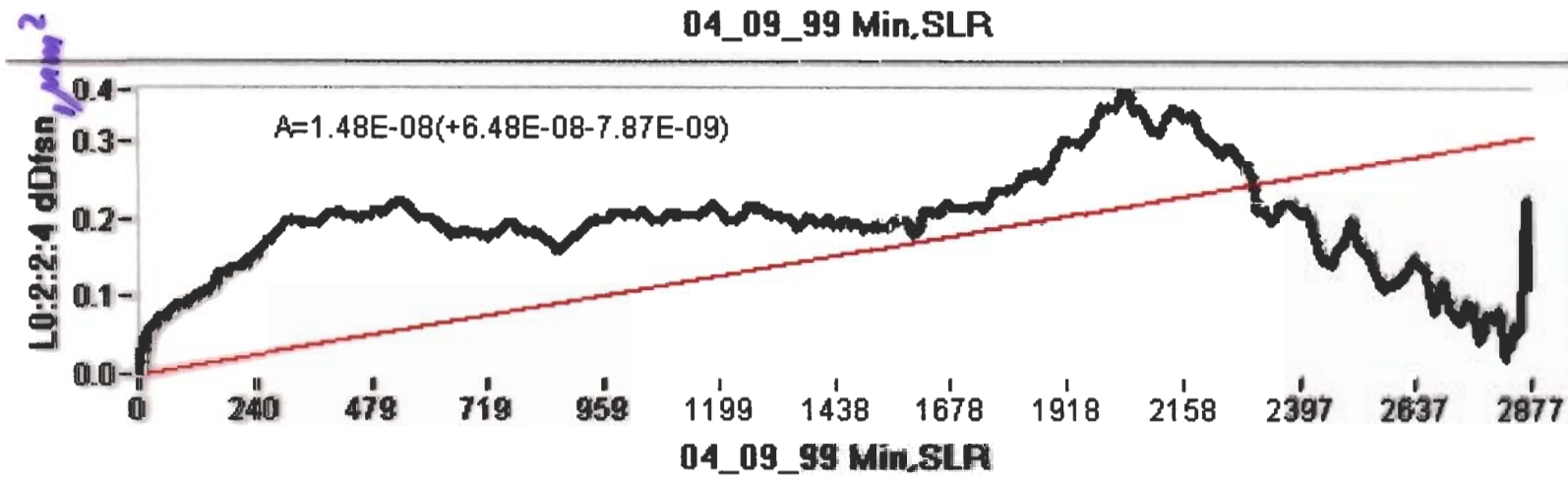
Amplitude of tide varies as Moon changes its position with respect to the Sun. Period of variations is 14 days.











Two days in sealed room, all HLSs are set side by side: "effective 30-meter" noise coeff.

$A = 1.5 \cdot 10^{-8} \frac{\mu m^2}{s \cdot m}$ (drifts excluded)

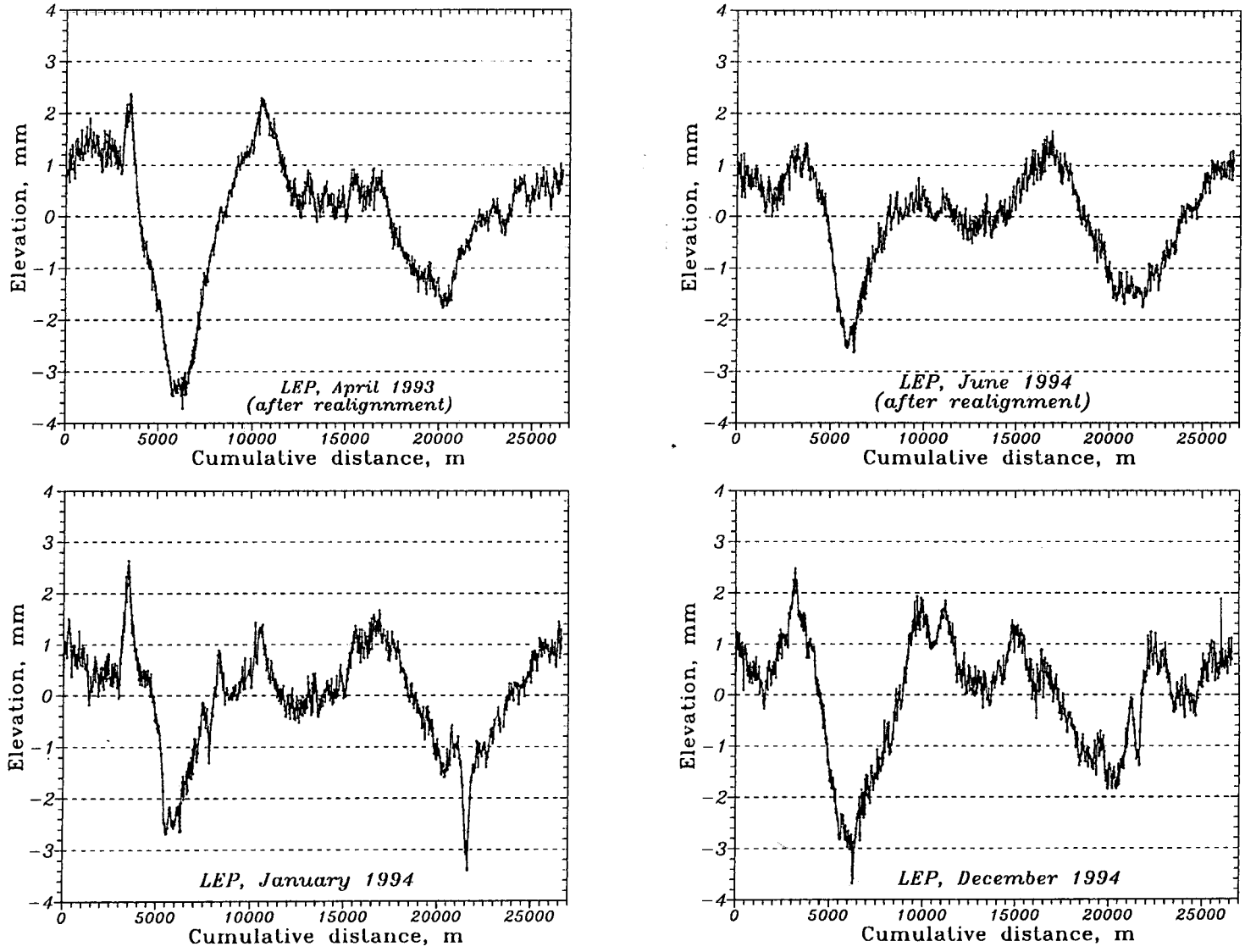


Fig.3 LEP elevations in 1993–1994 (from Ref.[17]).

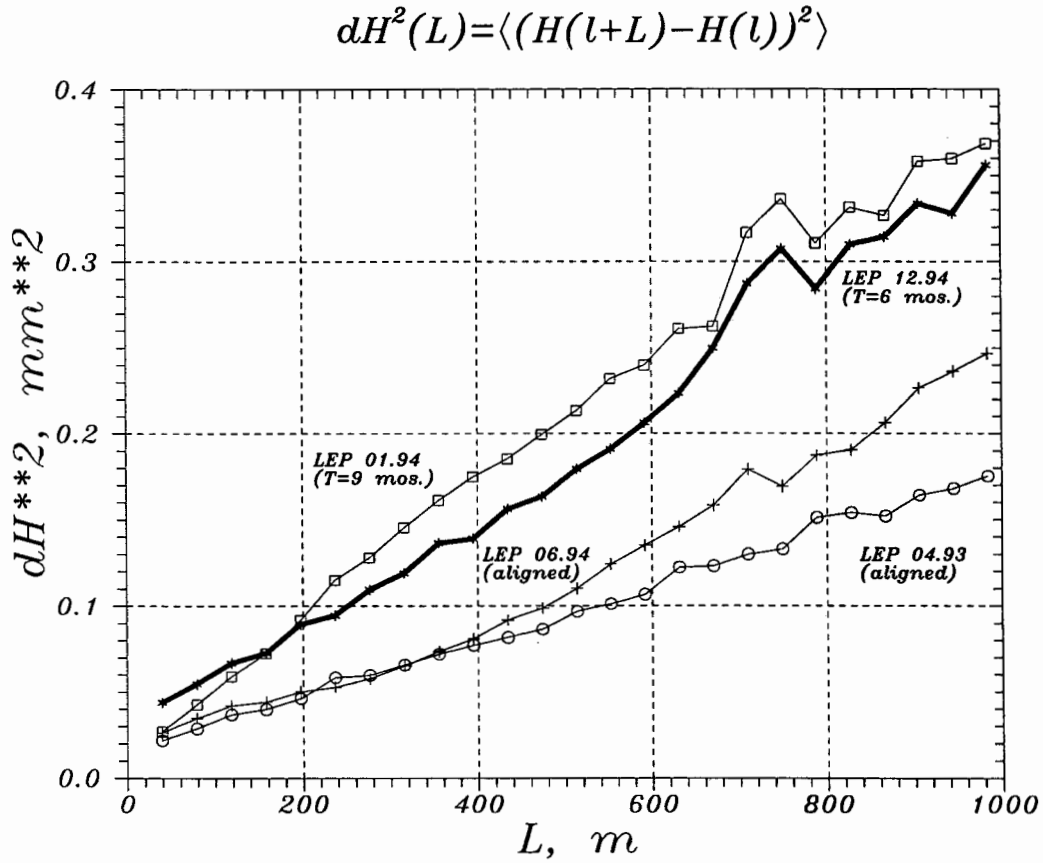


Fig.4 Mean squared height difference vs. L:
04.1993 – LEP is aligned, 01.1994 – 9 months after;
06.1994 – LEP is aligned, 12.1994 – 6 months after.

SLOW QUAD MOTION

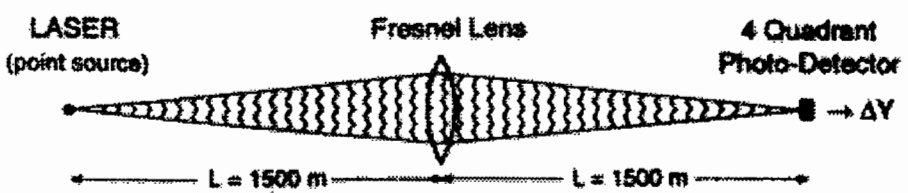
Characterize by 'ATL' Behavior: $\langle \Delta Y^2 \rangle = \underline{A} \times \underline{\text{Time}} \times \underline{\text{Length}}$

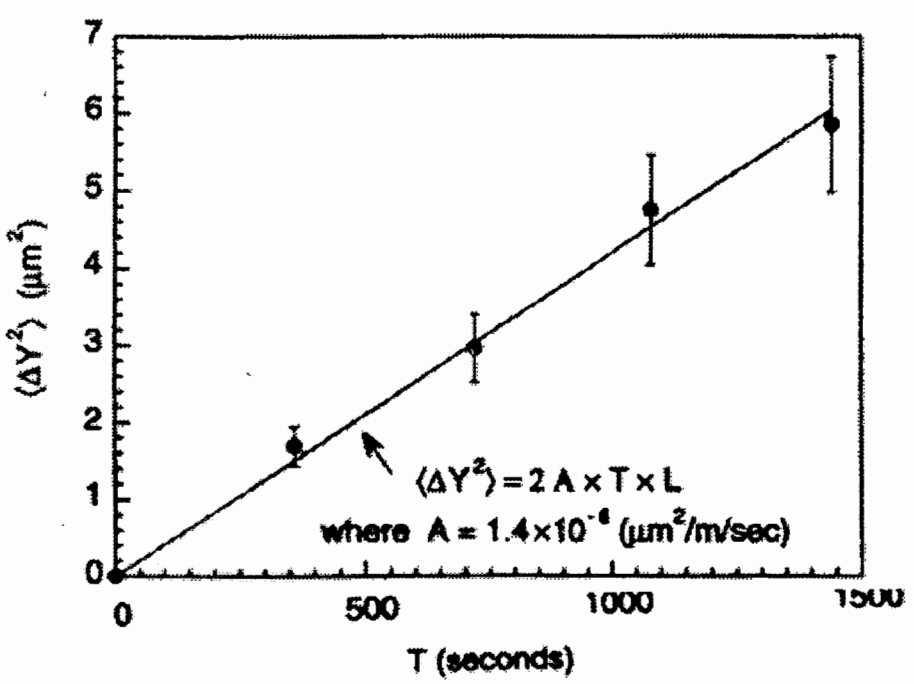
What is A ?

1) Infer upper limit from STS2 data: for T < 50 sec & L = 200 m

$$A < 2 \times 10^{-7} \ (\mu m^2/m/sec)$$

2) Measurements with SLAC's Linac Laser Alignment System





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Power Spectral Density

$$S_{ATL}(f) = \frac{A \cdot L}{2\pi^2 f^2} \quad \left[\frac{\mu m^2}{Hz}\right].$$

PSD of ORBIT DRIFTS in HERA $S(f) \propto \frac{2A \cdot C}{\pi^2 f^2}$

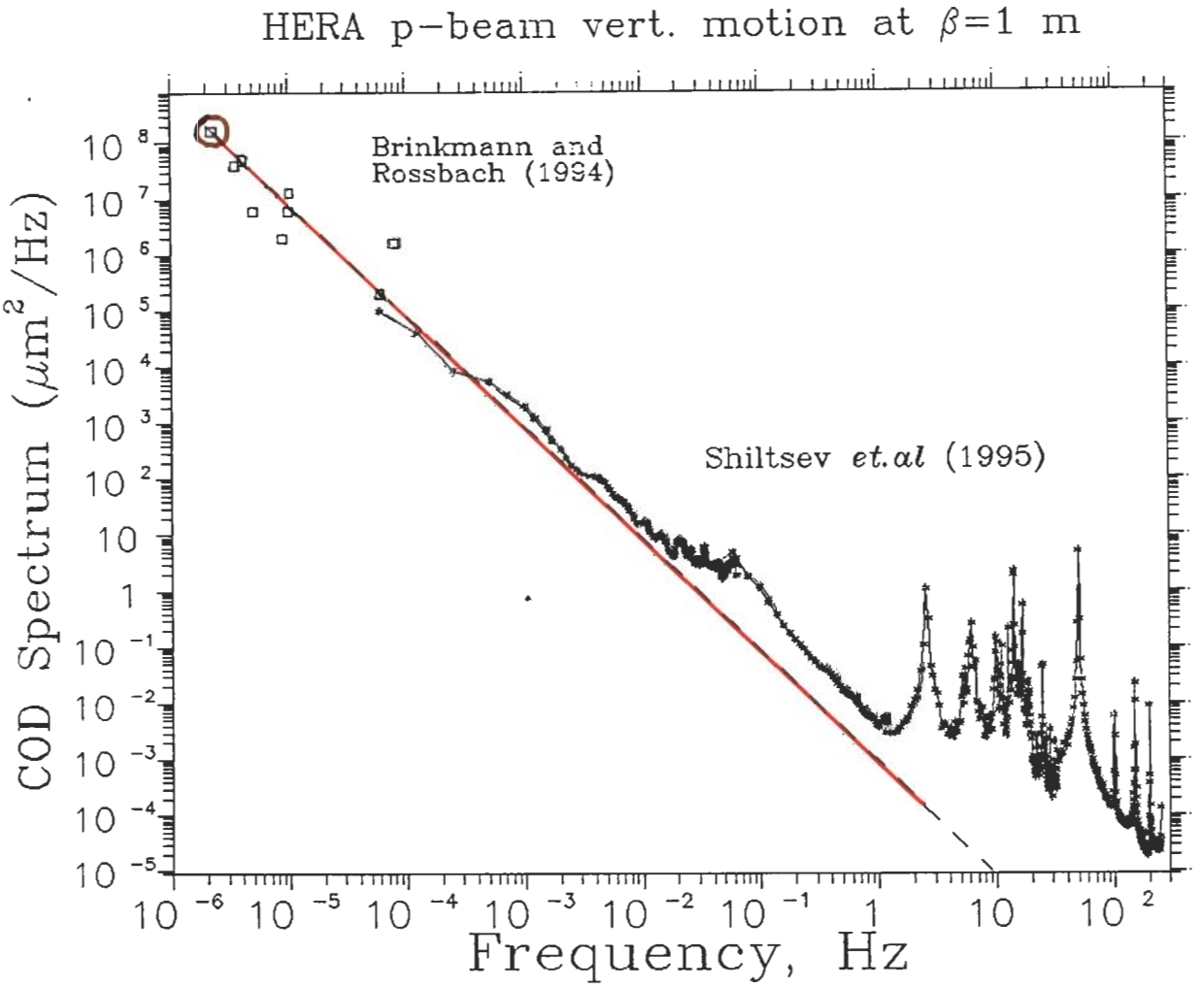

Fig.6 PSD of HERA proton orbit vertical motion normalized to β =1 m. Dashed line is for the ATL expectation (from Ref.[18, 9]).

$$\rightarrow A = (1.5 \pm 1.0) \cdot 10^{-5} \frac{\mu m^2}{s \cdot m}$$

e.g. point ⓐ corresponds to 14 μm @ β=1 m over period of 1 week
or 140 μm @ β=100 m

Table 2: Ground diffusion observations

Site	A, $10^{-5}\ \frac{\mu m^2}{s \cdot m}$	T	L		Depth
UNK, Protvino	10	2 yr.	50–500 m	V	0 m
UNK, Protvino	10±5	1–10 hrs.	5–10 m	V, H	0 m
SLAC Linac	20±10	17 yr.	50–1000 m	V	0–5 m
SLAC PEP	10±5	20 mos.	20–200 m	V	~10
PS pillar	0.2÷0.4	2.5 yr.	10 m	H	0 m
SPS CERN	1÷1.4	3–12 yr.	60 m – 2 km	V	~20 m
LEP CERN	0.7÷0.9	9 mos.	40 m – 1 km	V	≥30 m
Pinon Flat	0.01	1 yr.	24 m	H	0 m
TRISTAN KEK	0.5/0.04	4 days	42.5 m/12.5 m	V	12 m
Sazare mine	0.001÷0.015	1 week	48 m	V	300 m
Esashi station	0.033±0.005	0–4 yr.	50 m	V	60 m
Orbit of TRISTAN	4.3±3	2 days	~20 m	V	12 m
Orbit of HERA-p	1.5±1	1 s – 5 days	~50 m	V	~25m
Orbit of HERA-e	0.4±0.1	1 s – 1 month	~24 m	V	~25 m

4.2 Validity Limits of the ATL Law

The question of the limits of applicability of the ATL law is still open. Fig.14 presents spatial and temporal intervals where the diffusion was observed. Without any doubt, typical L and T intervals at accelerators are within these limits – and the orbit drifts at HERA and TRISTAN have proved that. Nevertheless, obviously, the law should not work at small time intervals T for rather large separation length L due to independence of movements of the points, but only further investigations of slow drifts will allow us to clear the issue.

Concluding of this section, I would like to mention that at the present time there are some evidences of the diffusion at much larger $T - L$ intervals. For example, on the base of 50 years observation (1930–1980) at 12 points of Japan coast [23], there was found in [24] that besides daily and seasonal variations, the sea level (or, Japanese islands elevation) demonstrates some long-term "random walk" behaviour. Figs.15 a) b) show half-century sea level records measured at two Japan ports distanced by L =800 km.

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At present time, there're about 20 experiments where the ground diffusion in space or/and in time was detected (see Review in IWAA'95 Proc.).

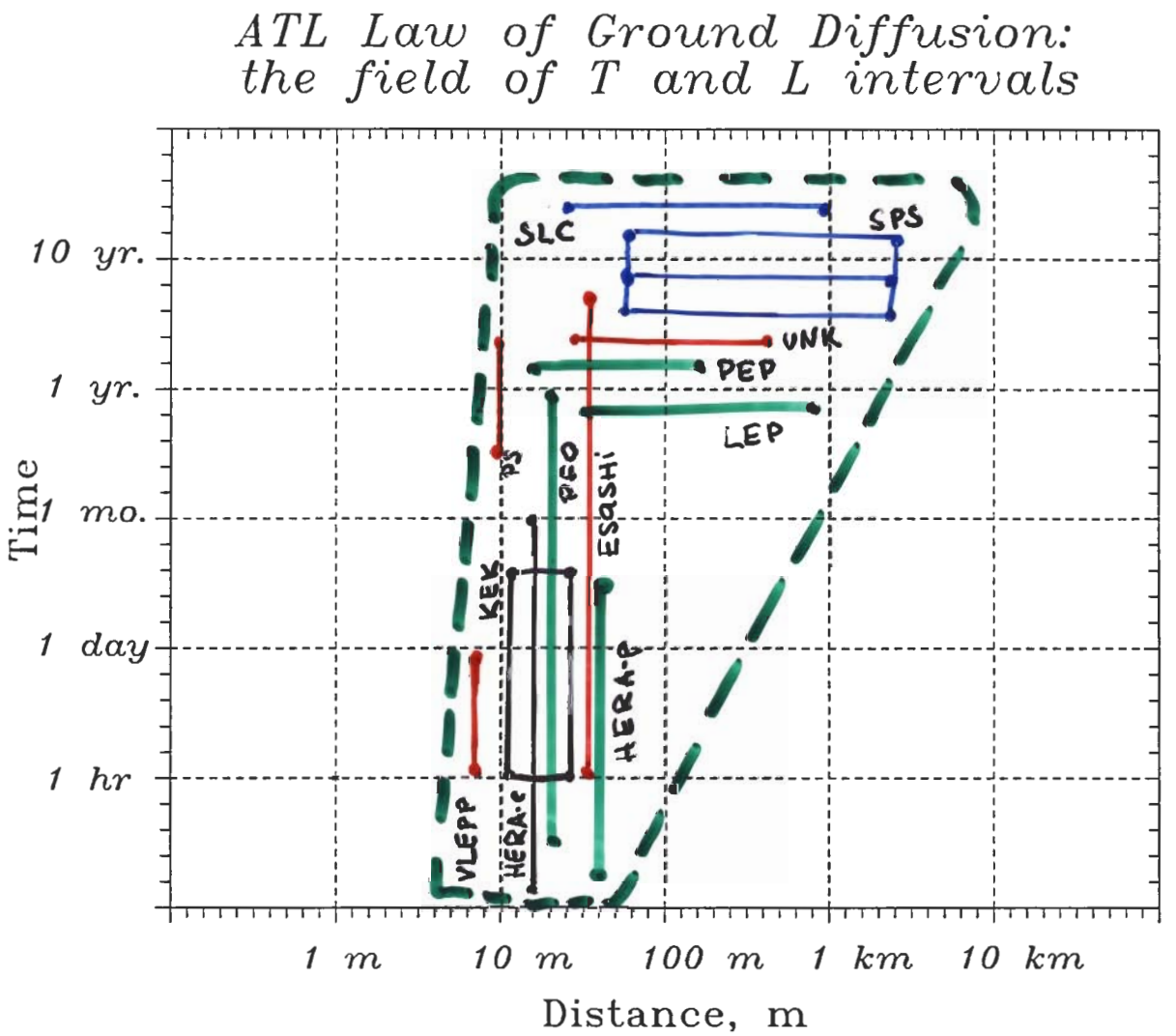
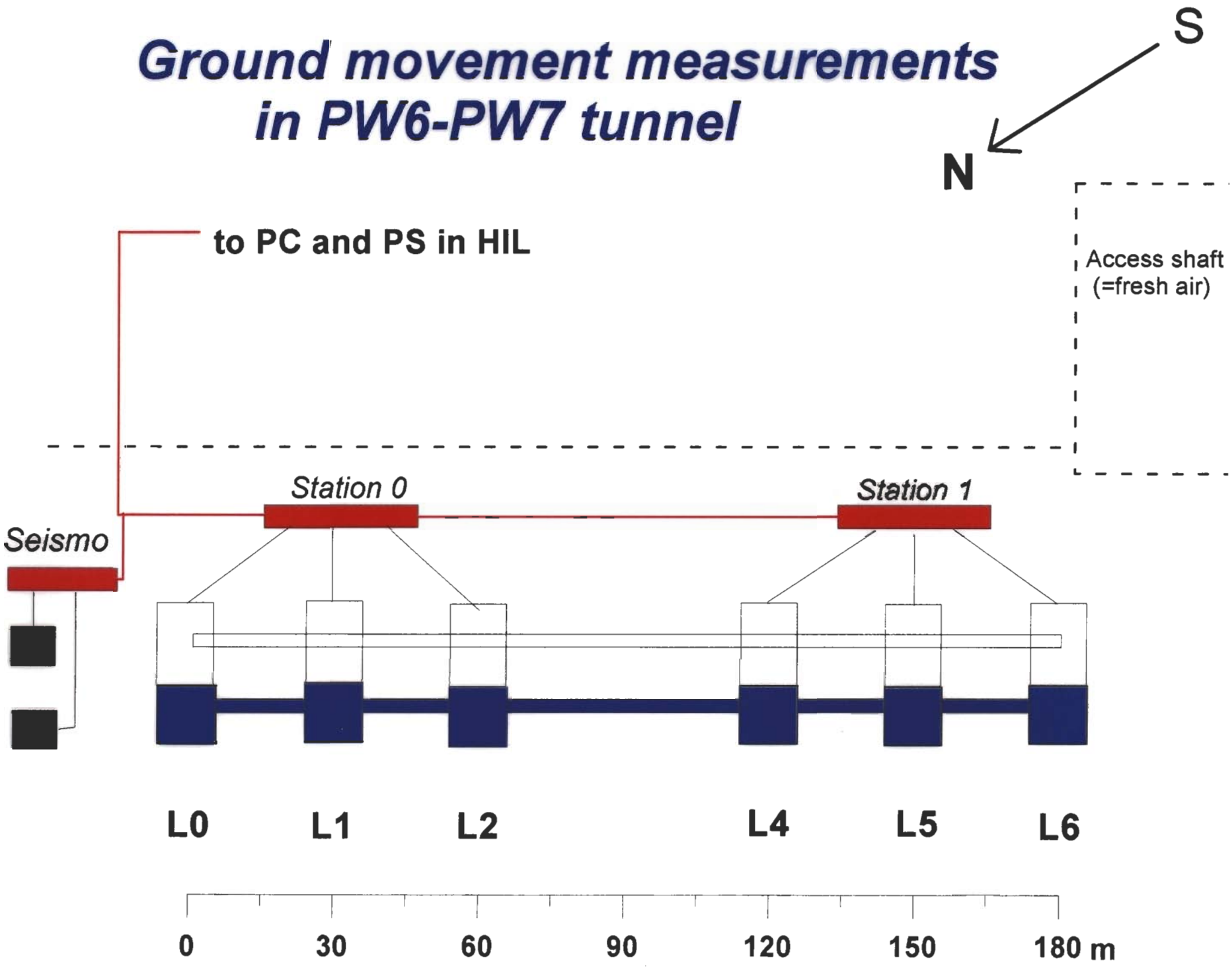
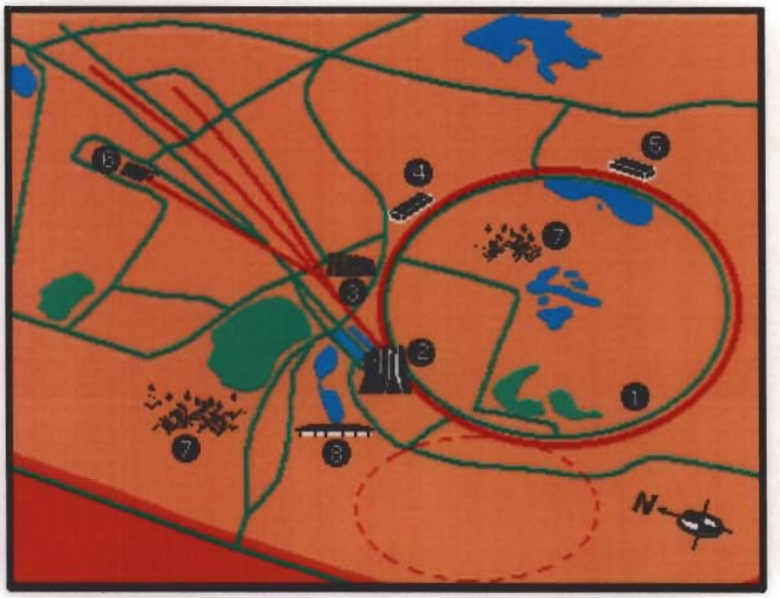


Fig.14 The intervals of T and L where the ground diffusion was experimentally detected.

Ground movement measurements in PW6-PW7 tunnel



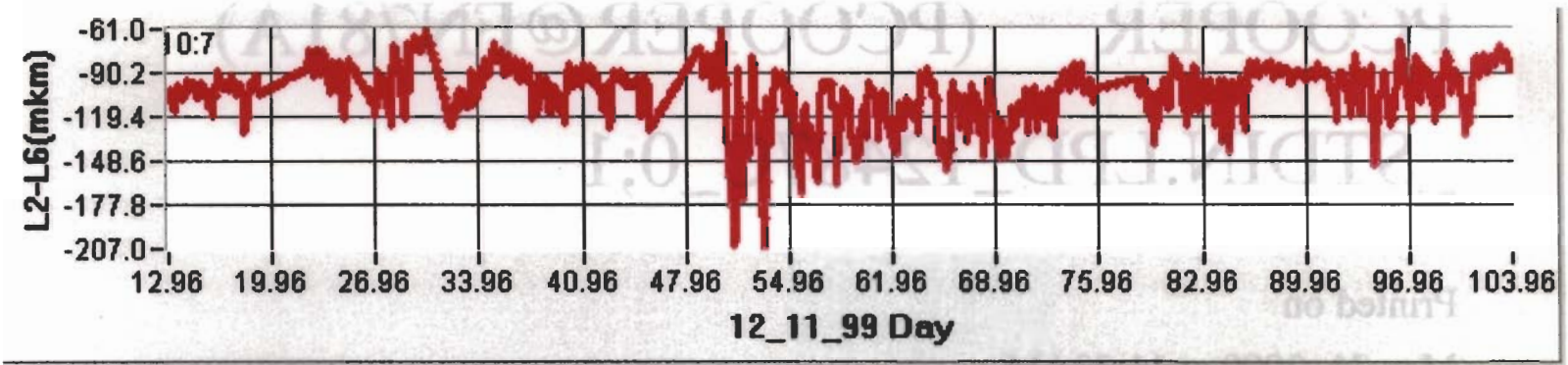
Fermilab PW6-7 "cut-and-cover" tunnel

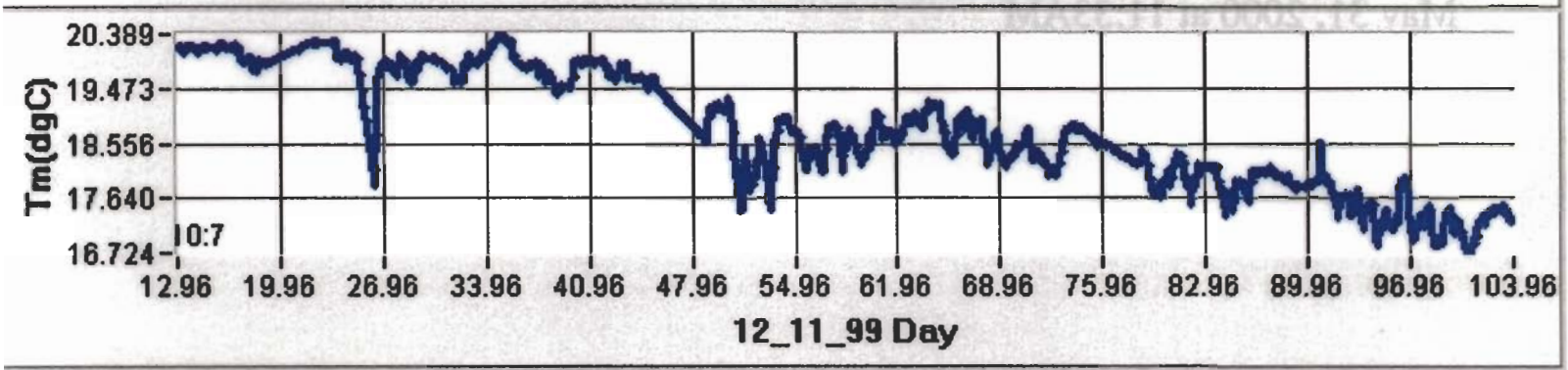


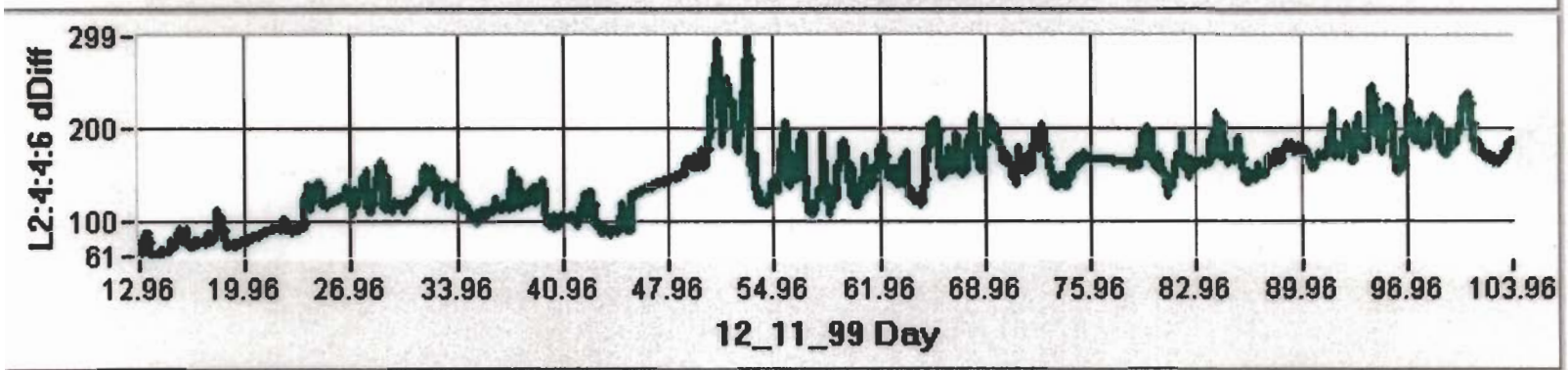
Distance L=30-180 meter Time T=1min-3mos

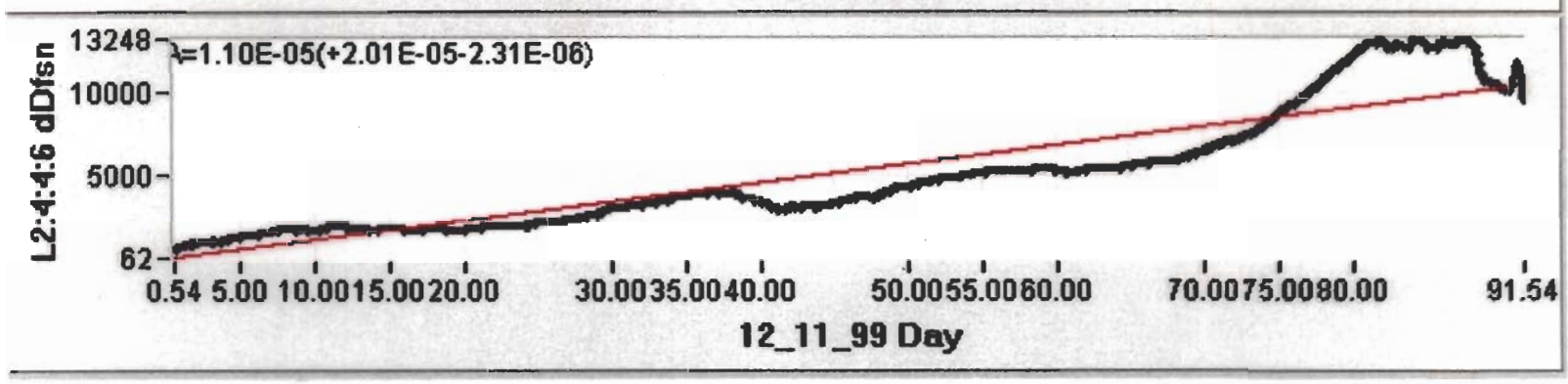
Diffusion Coefficient A in Units of 10^{-6} [$\mu m^2/s/m$]

Set of sensors	"whole" A	"-t^o "	"-Lin.drifts"	"-t^o-LD"
L=30 m	temperature variation dT°=5 °C			
0-1-1+2	5.3	1.1	0.57	0.57
4-5-5+6	8.4	7.7	2.2	2.2
L=60 m				
0-2-2+4	1.0	0.82	0.9	0.8
2-4-4+6	11	11	1.5	1.5
< A >	6.4	5.1	1.3	1.2



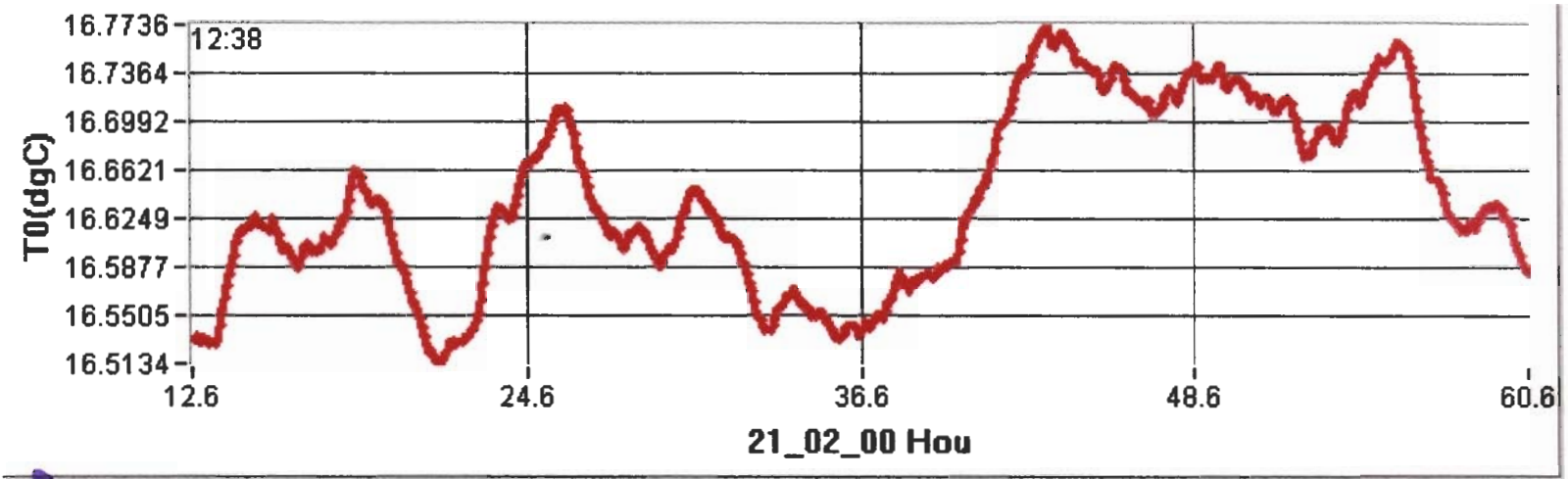


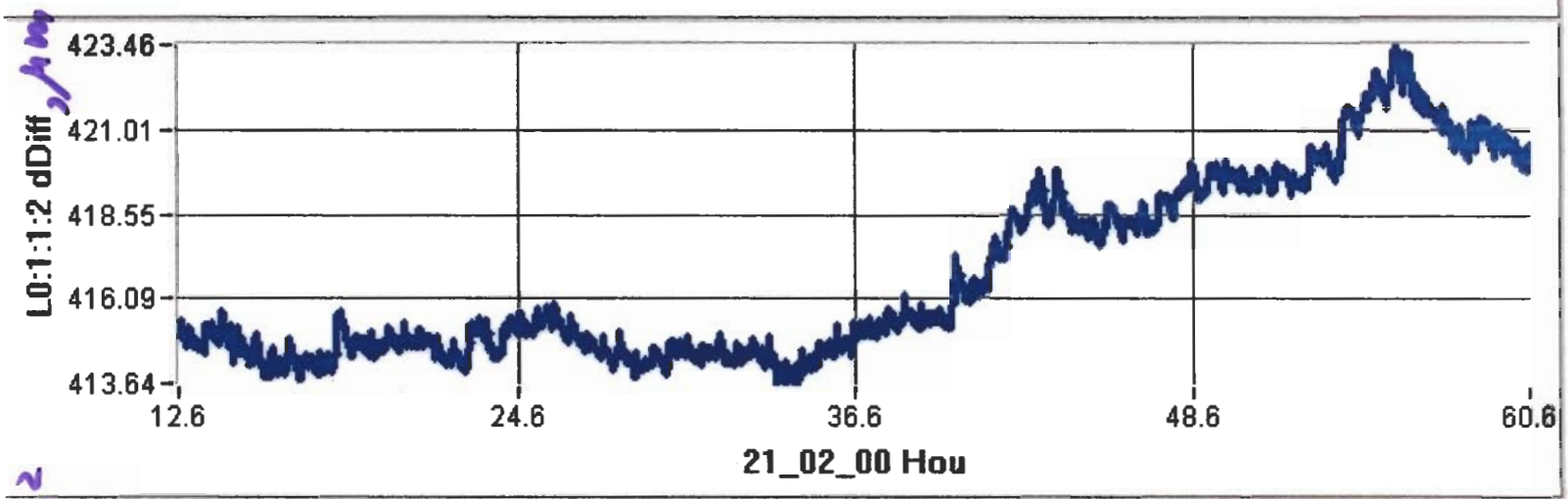


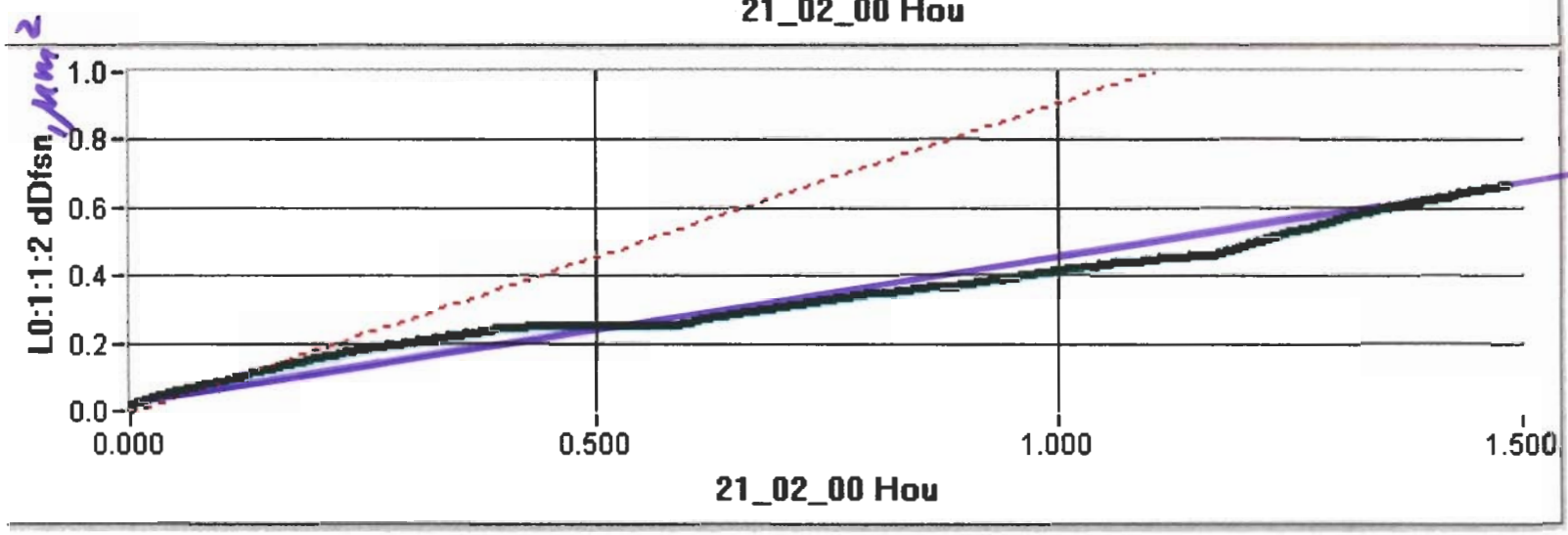


3 MONTHS record of PW6-7 "cut-and-cover" tunnel on FNAL site (11-12-99 — 02-11-00): top-probes 120 m apart then - average T°; 2nd from bottom = (L2-L4)-(L4-L6) = the second difference bottom plot: mean of the 2nd difference squared

red line indicates ATL WITH $A = 11 \times 10^{-6} \frac{\mu m^2}{m \cdot s}$







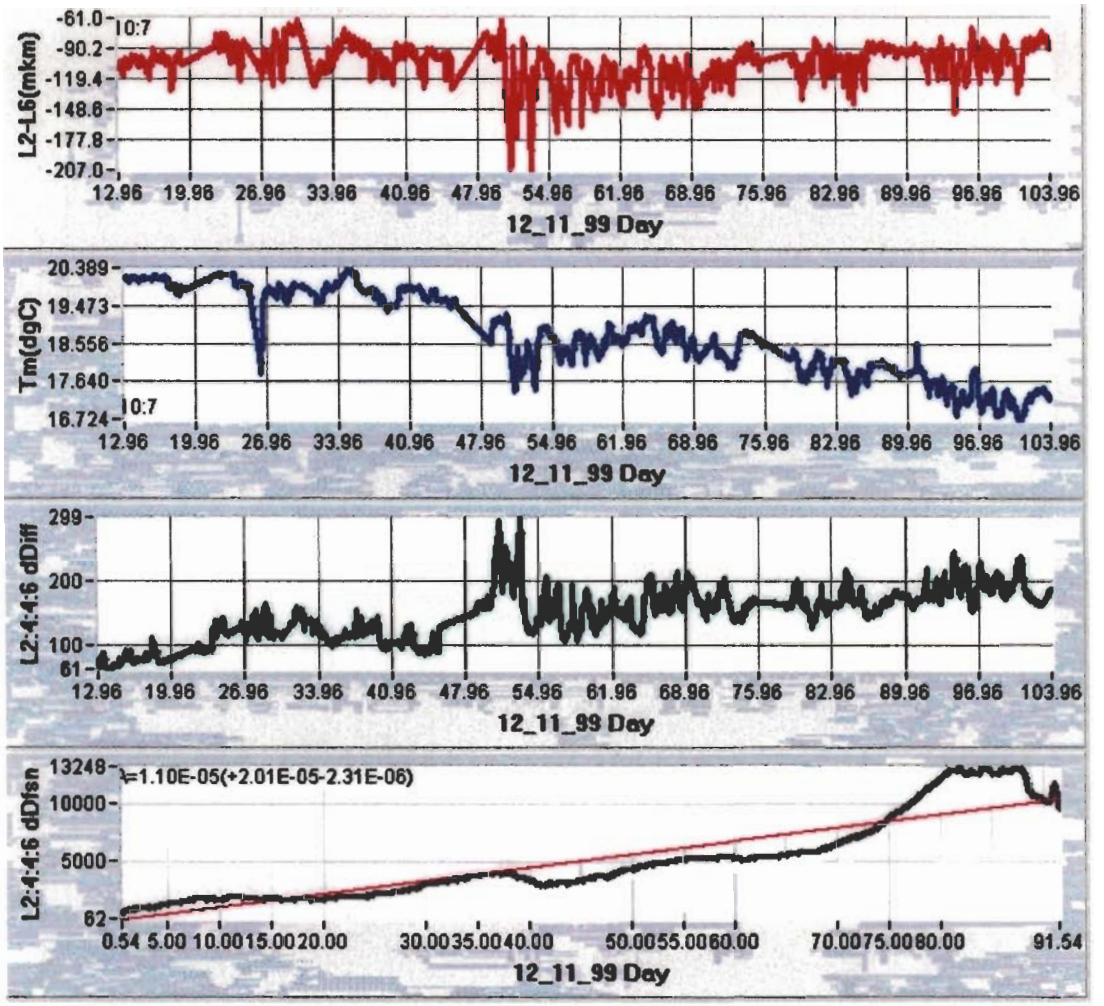
2 "Quiet" days in PW tunnel ($\Delta T° \sim 0.3°C$ - top plot)

MIDDLE: 2nd differens $ddH = (L1-L2)-(L0-L1)$ (in μm)

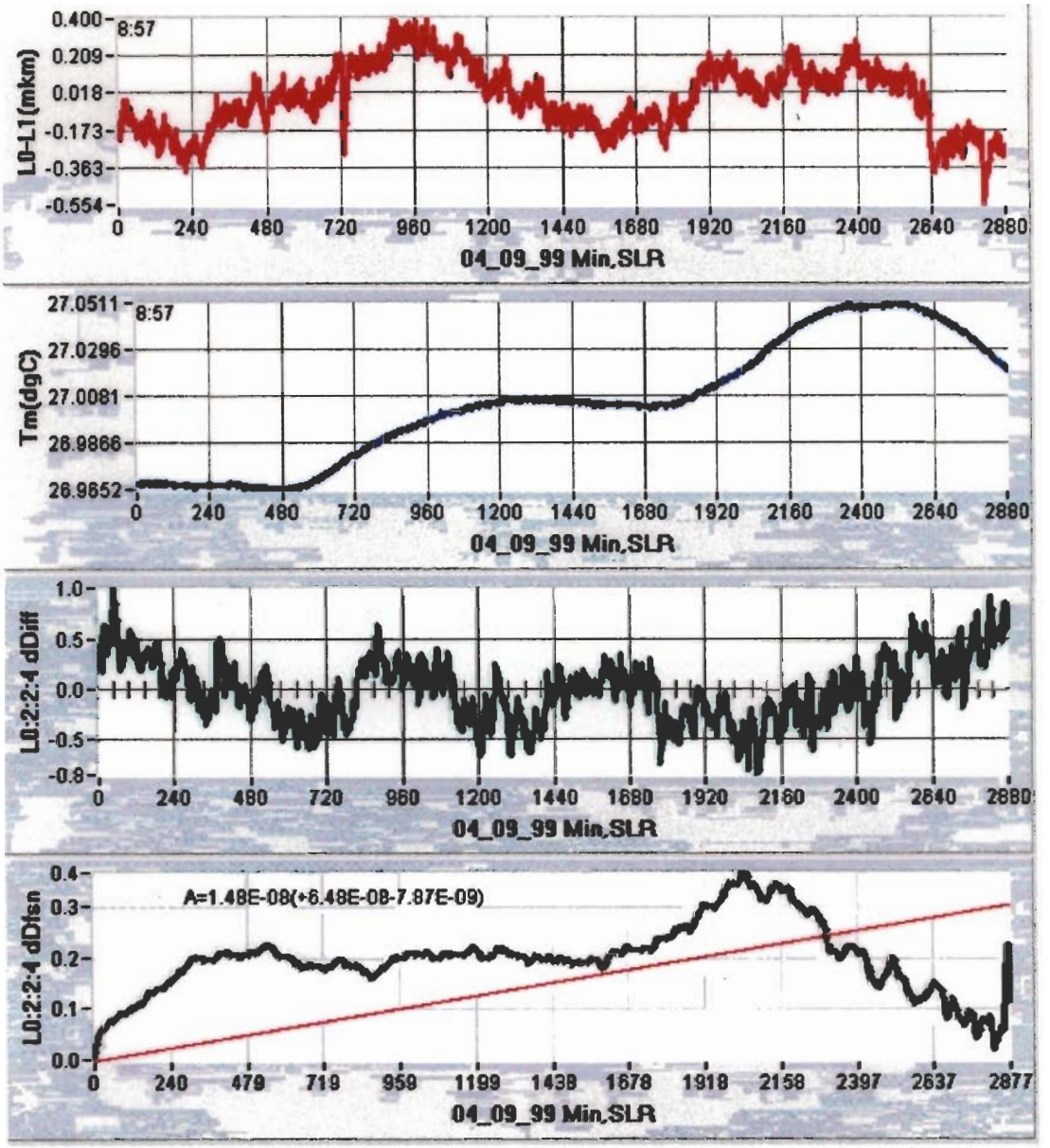
BOTTOM: Mean square $\langle ddH^2 \rangle$ in μm^2 for $\Delta T = 0 \ldots 90$ min

STRAIGHT LINE indicates AT^2 WITH $A = 2.1 \cdot 10^{-6} \frac{\mu m^2}{m \cdot s}$

DASHED LINE - Linear fit WITH $A = 4.2 \cdot 10^{-6}$ for $\Delta T = 0 \ldots 48$ hrs

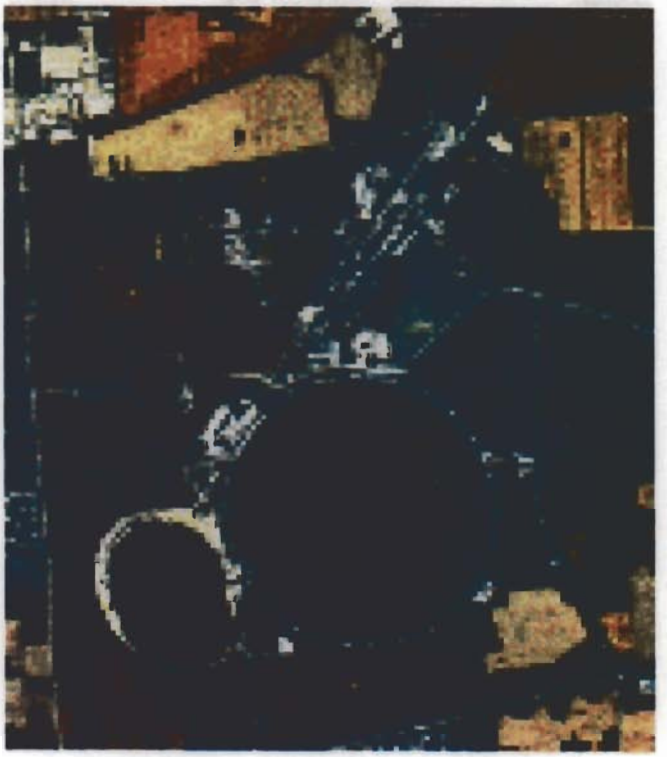


Three months record of ground motion in FNAL PW6-7 tunnel (Nov. 12, 1999 – Feb. 11, 2000). Top plot – elevation difference of probes L2 and L6 (120 m apart) dH=L2-L6; second from top – average temperature of water in all probes; third from top - "fracture" (slope difference) of elevations of sensors ddH=(L2-L4)-(L4-L6); bottom – duffusion <ddH^2> vs time dT (in days), red line corresponds to the ATL law with A=1.1*10^-5 um^2/m/s.



Two days record of water levels in lab conditions, HLS probes side by side (Saturday, Sept. 4, 1999, 9 a.m. – Monday, Sept. 6, 1999, 9 am). Top plot – elevation difference of probes L0 and L1 dH=L0-L7, below – mean temperature of 5 HLSs, third from the top - "fracture" (slope difference) of elevations of sensors ddH=(L0-L2)-(L2-L4); bottom – duffusion <ddH^2> vs time dT (in min), red line corresponds to "effective ATL law" with A=1.48*10^-7 um^2/m/s as if the distance between probes L0 and L4 is 120 m.

Fermilab PW6-7 "cut-and-cover" tunnel



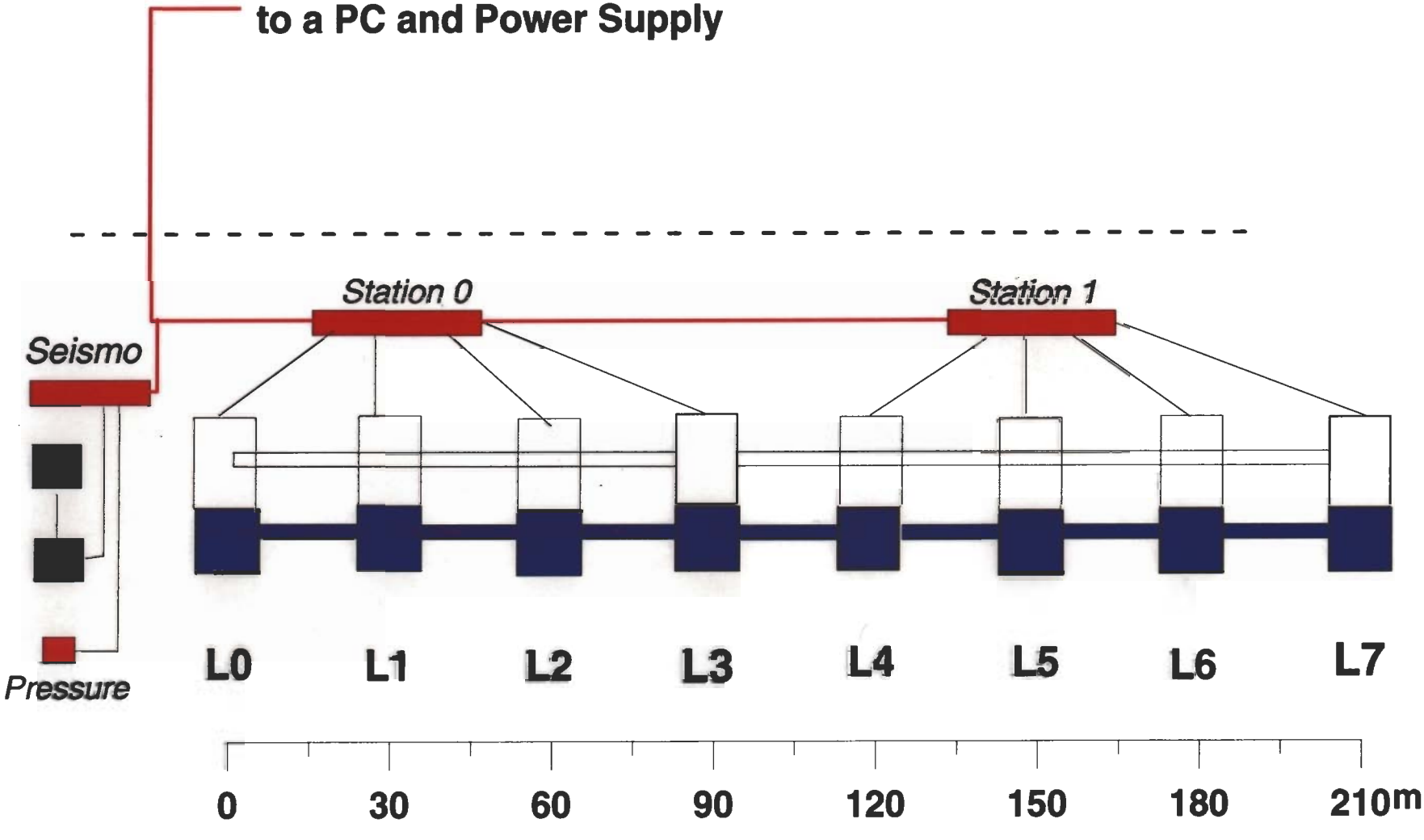
$\Delta t^\circ \sim 5^\circ C$

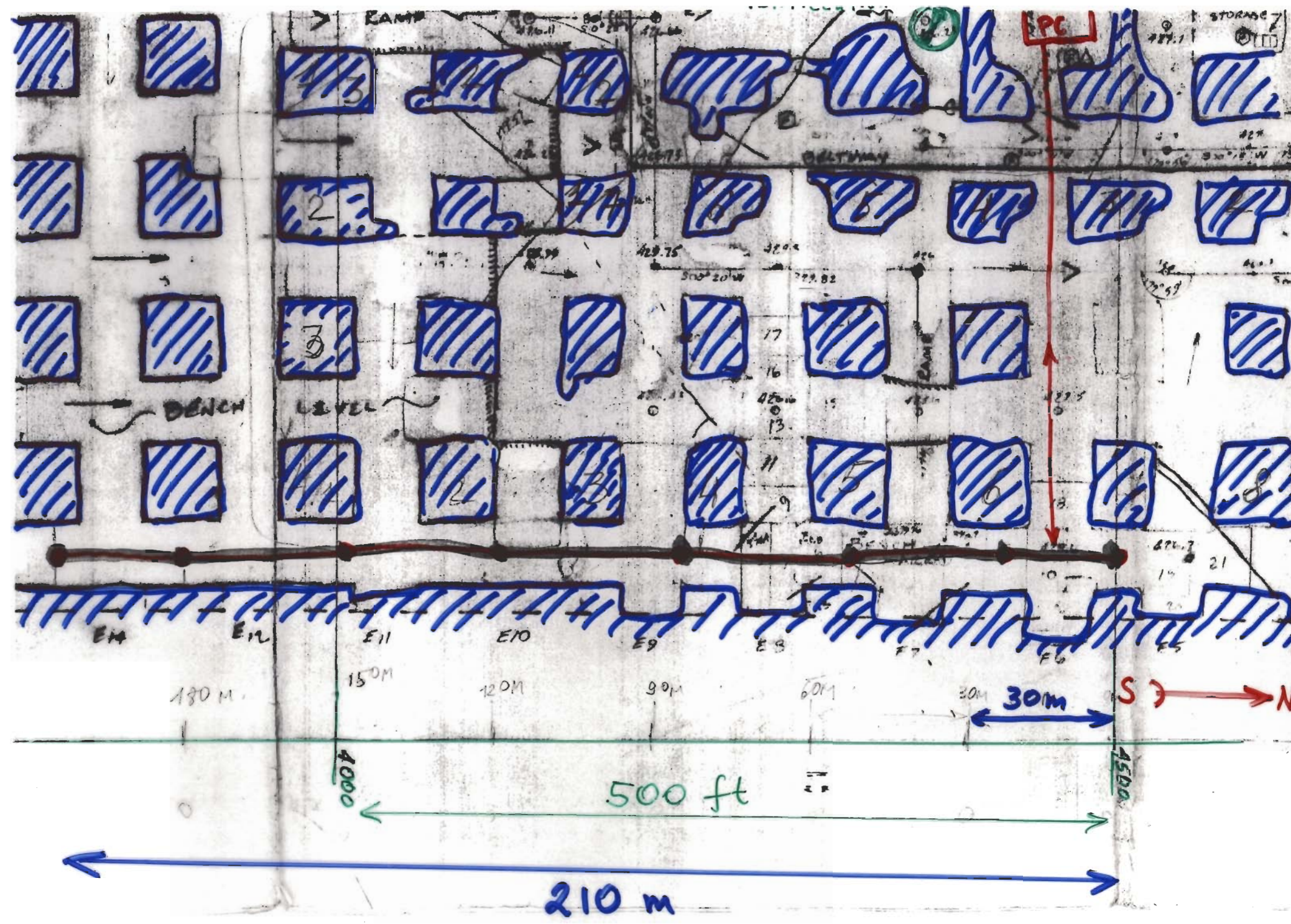
Distance L=30-180 meter Time T=~~1min~~-3mos

Diffusion Coefficient A in Units of 10^{-6} [$\mu m^2/s/m$]

Set of sensors	"whole" A	"-t^o"	"-Lin.drifts"	"-t^o-LD"
L=30 m				
0-1-1+2	5.3	~~5.3~~ 1.1	0.56	0.55
4-5-5+6	8.4	7.7	2.2	2.2
L=60 m				
0-2-2+4	1.0	~~0.9~~ 0.82	0.9	0.8 0.86
2-4-4+6	11	11	1.5	1.5
< A >	6.4	~~6.2~~ 5.1	1.3	1.2

Scheme of Ground Motion Measurements in Aurora Mine and FNAL PW Tunnel

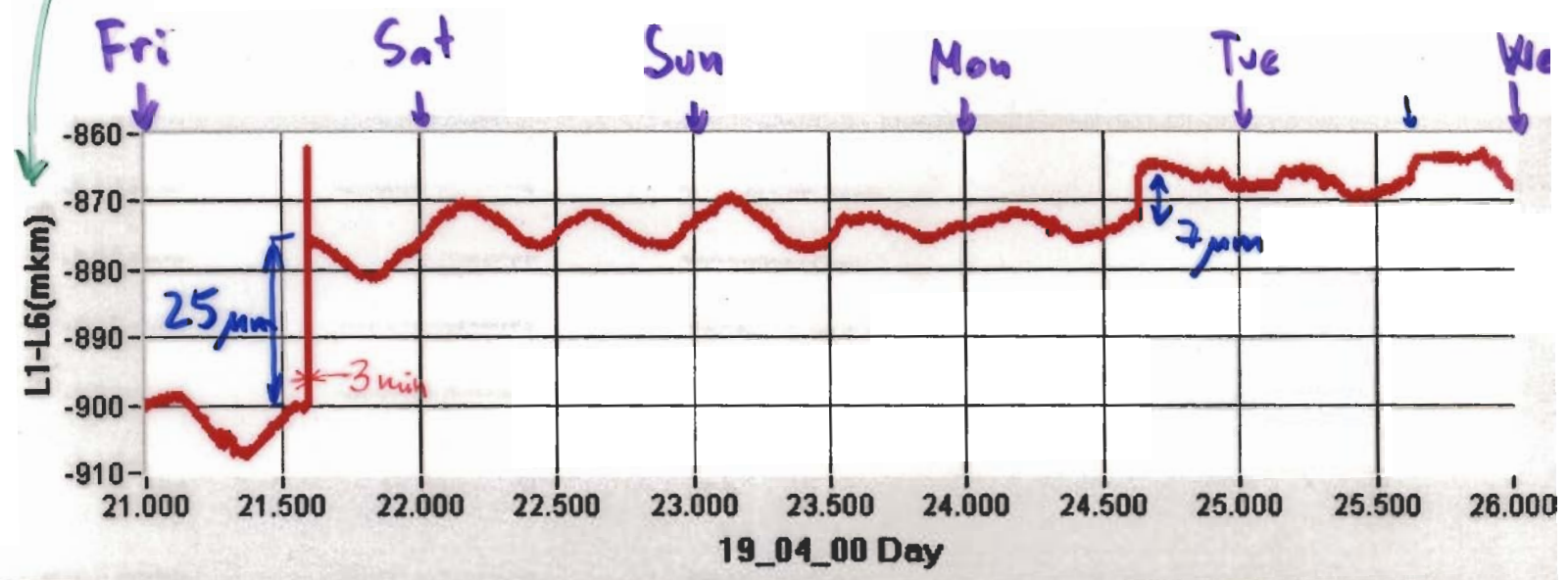


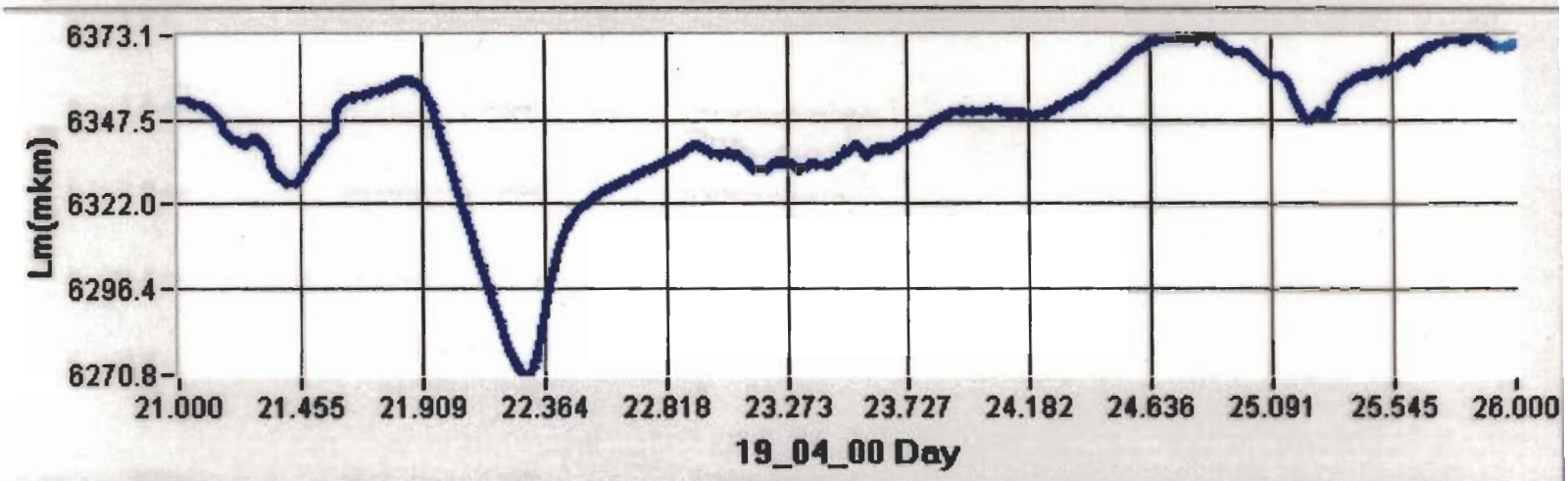


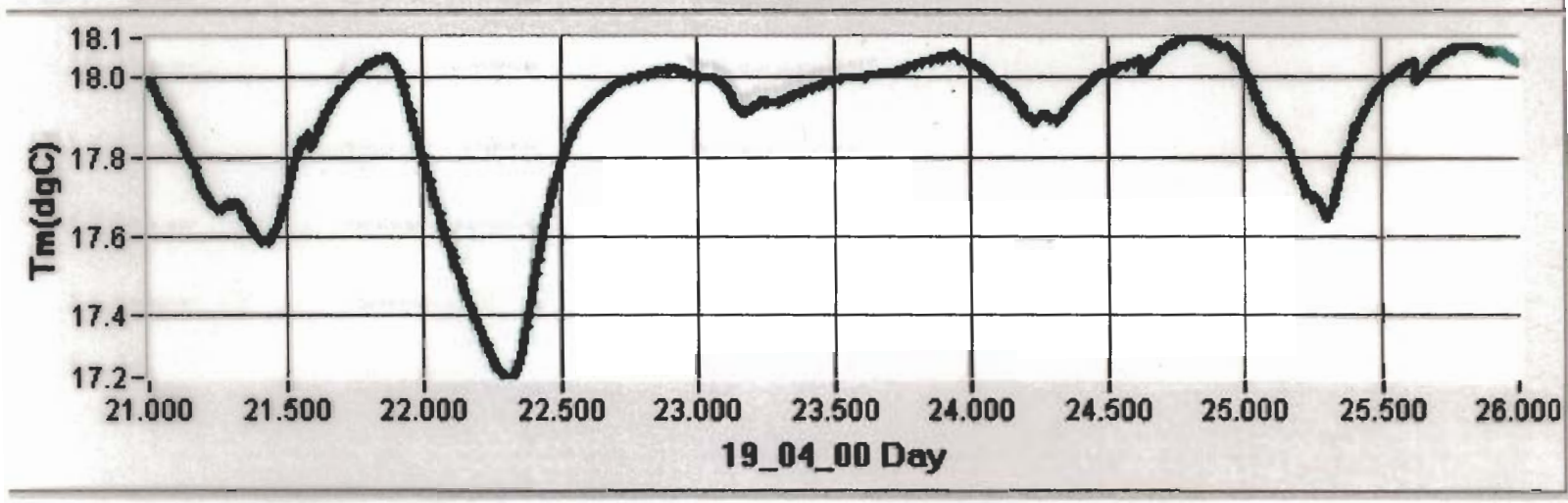
Conco Western mine Aurora TI

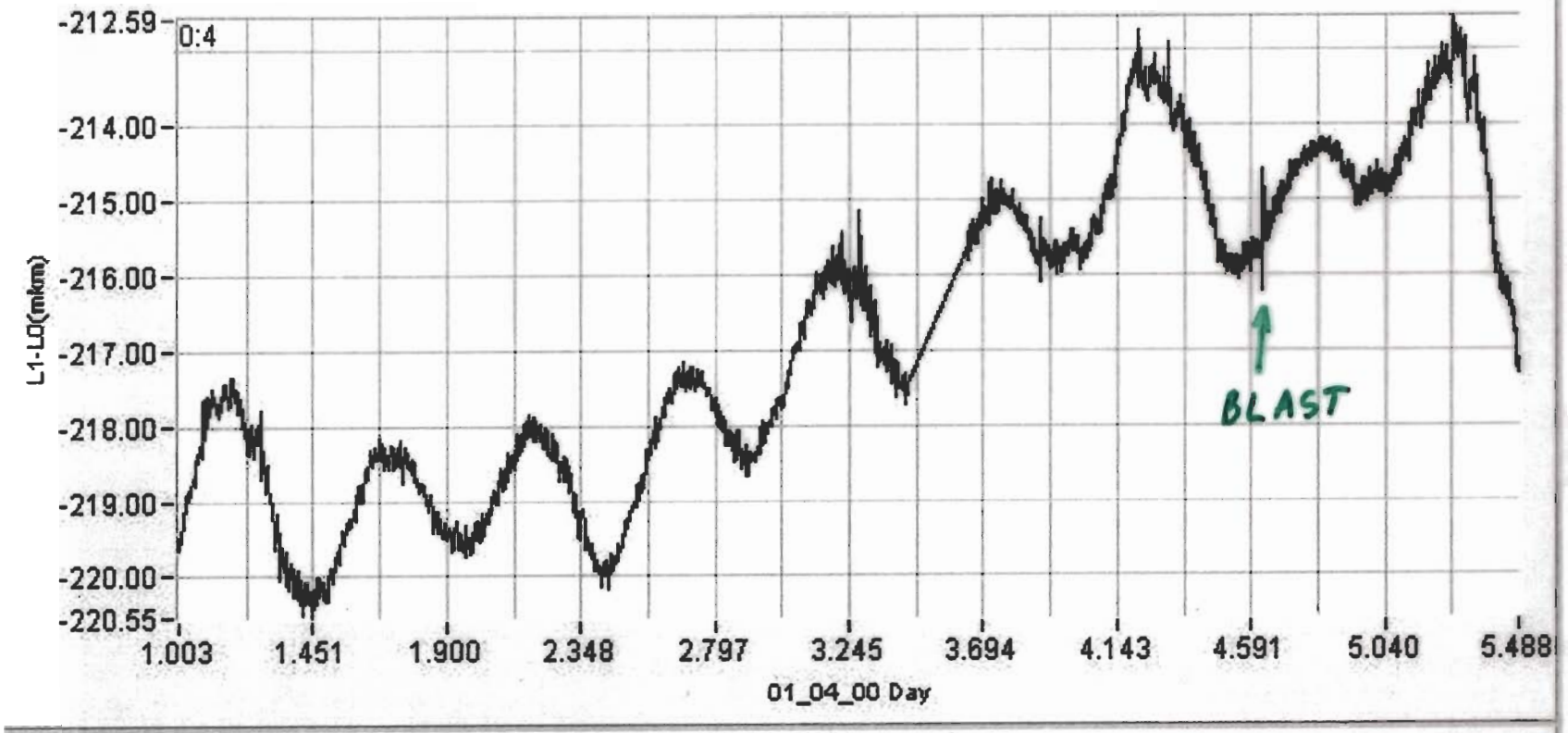
BLASTING in Aurora mine

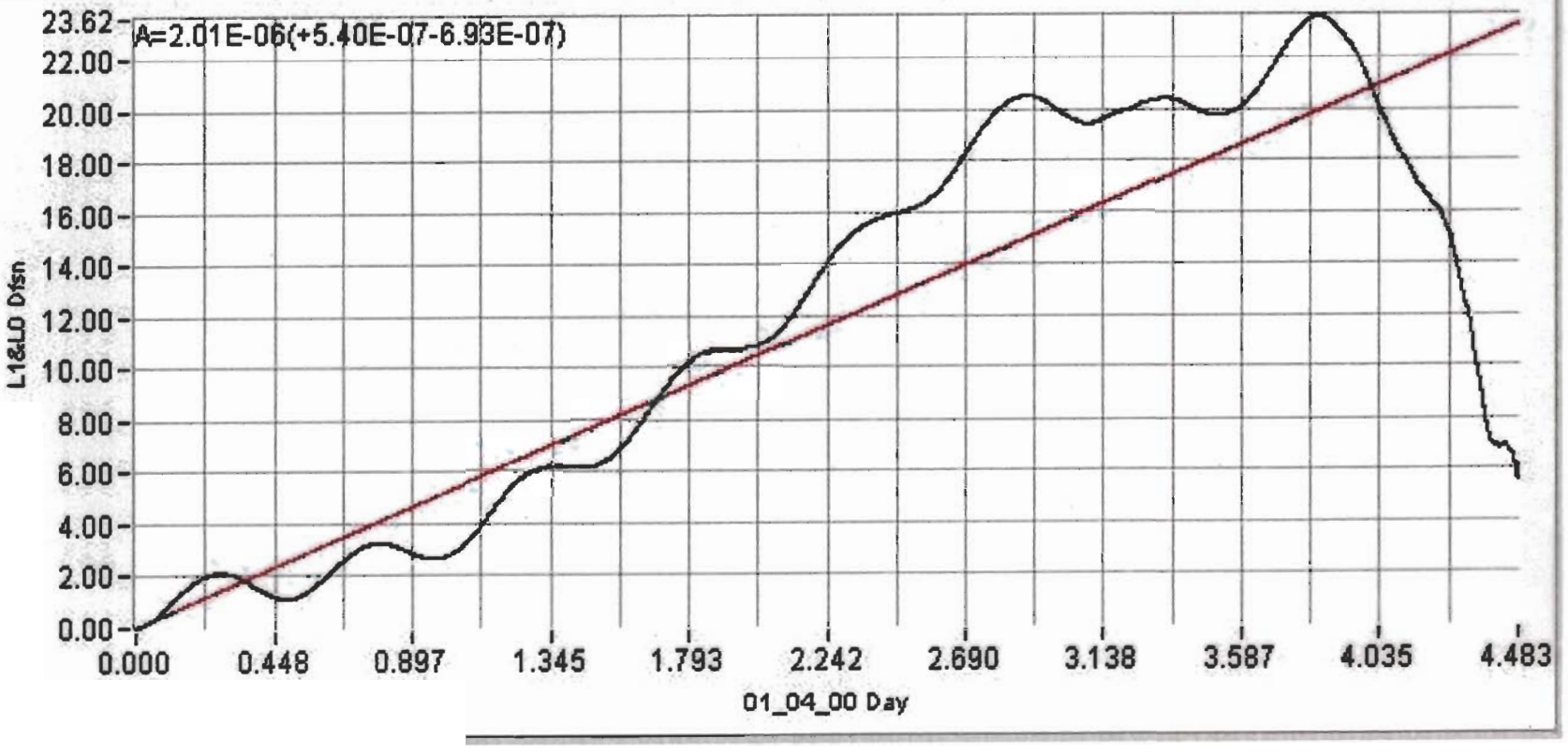
L=150m

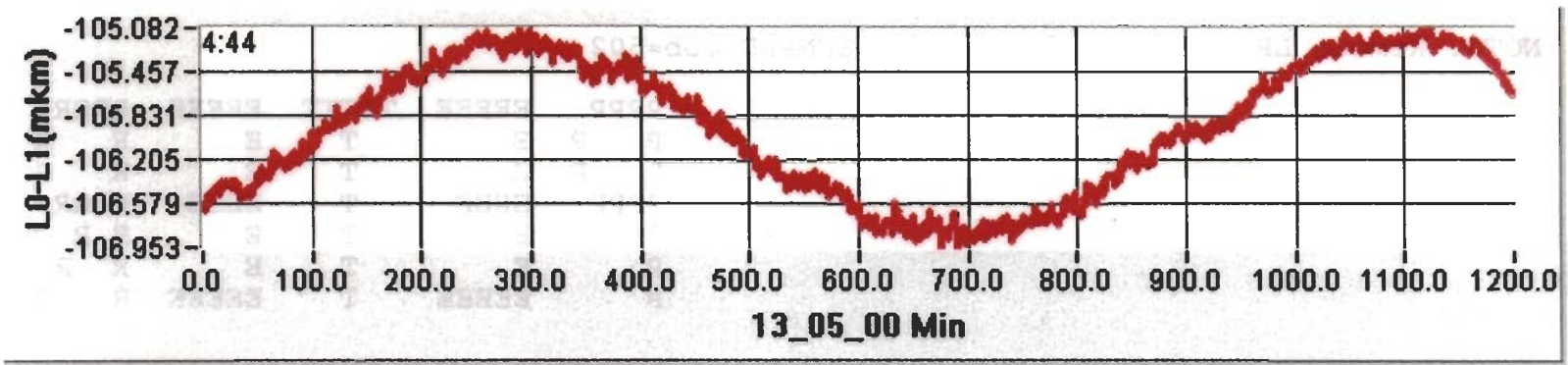


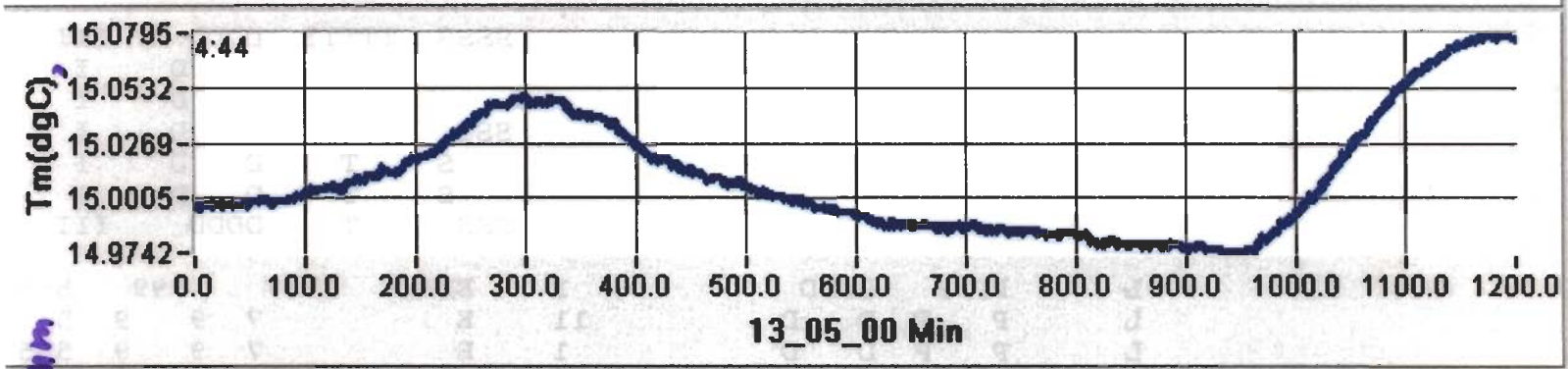


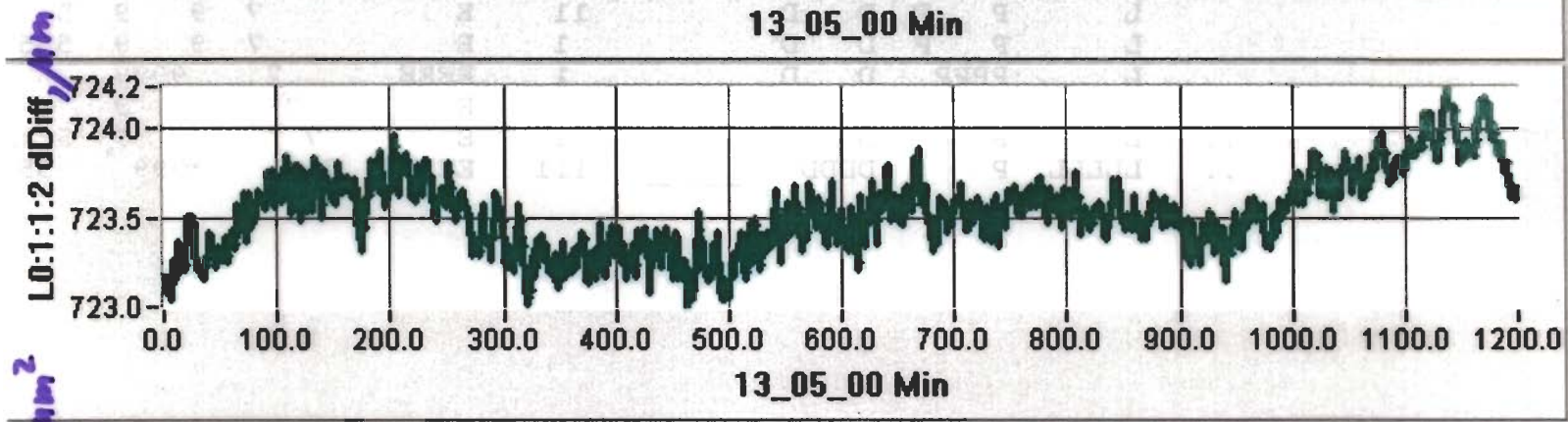


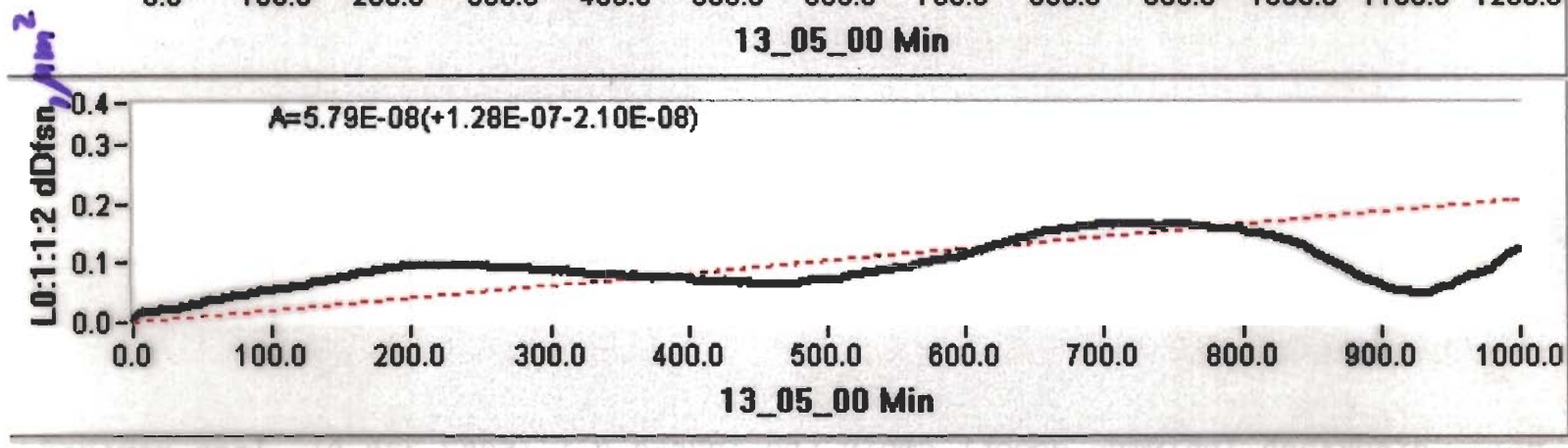

0:4
L1-LO(mkm)
-212.59
-214.00
-215.00
-216.00
-217.00
-218.00
-219.00
-220.00
-220.55
1.003
1.451
1.900
2.348
2.797
3.245
3.694
4.143
4.591
5.040
5.488
01_04_00 Day
BLAST


A=2.01E-06(+5.40E-07-6.93E-07)
L1&LO Dfsn
23.62
22.00
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0.000
0.448
0.897
1.345
1.793
2.242
2.690
3.138
3.587
4.035
4.483
01_04_00 Day







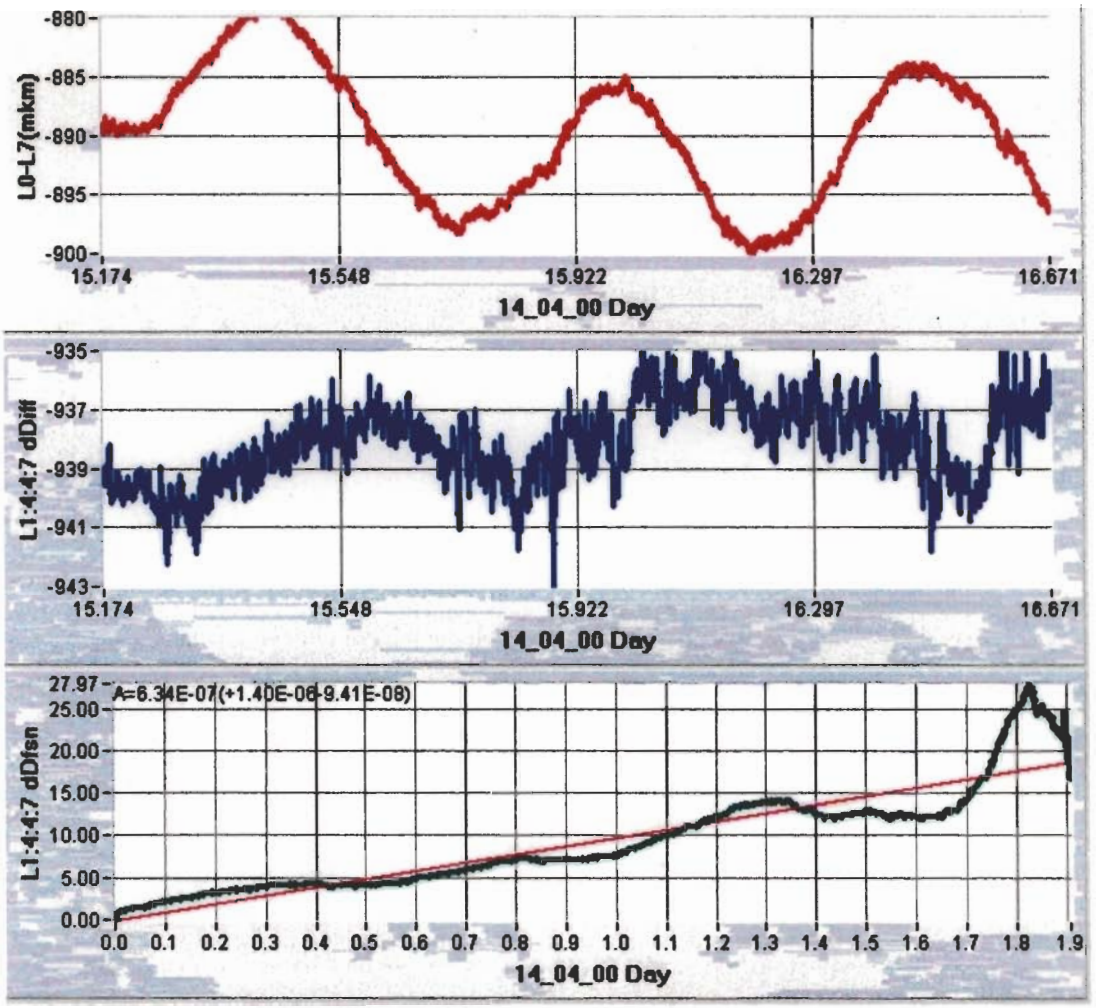


A very "Quiet" day in Aurora mine (13 May, 2000 - Sat)

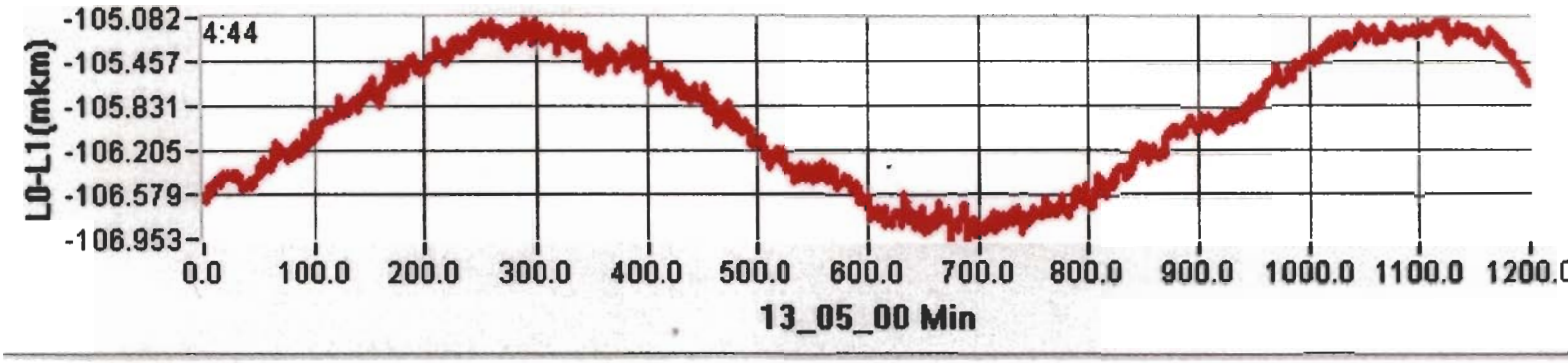
$\Delta T^\circ \sim 0.1^\circ C$, No blasts

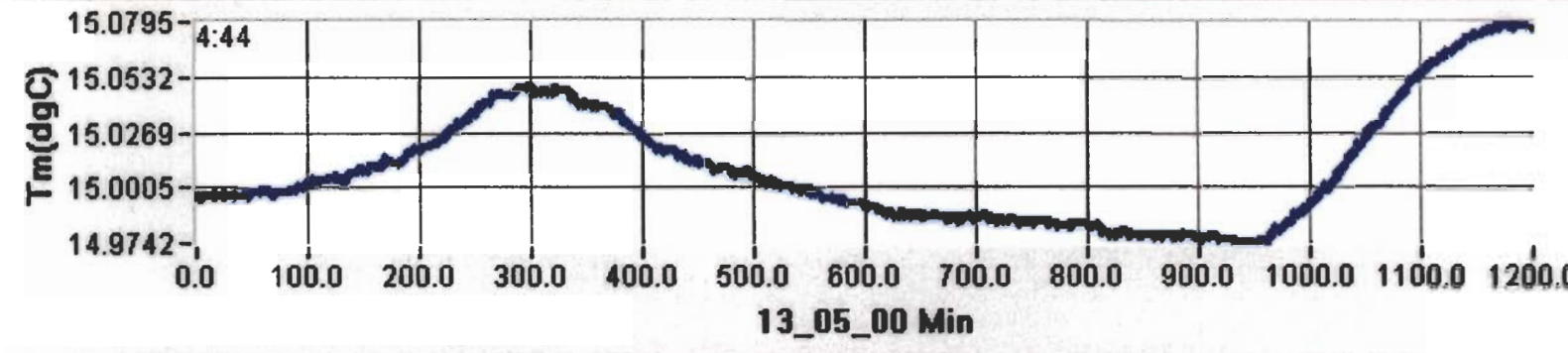
Red dashed line indicates ATL motion with

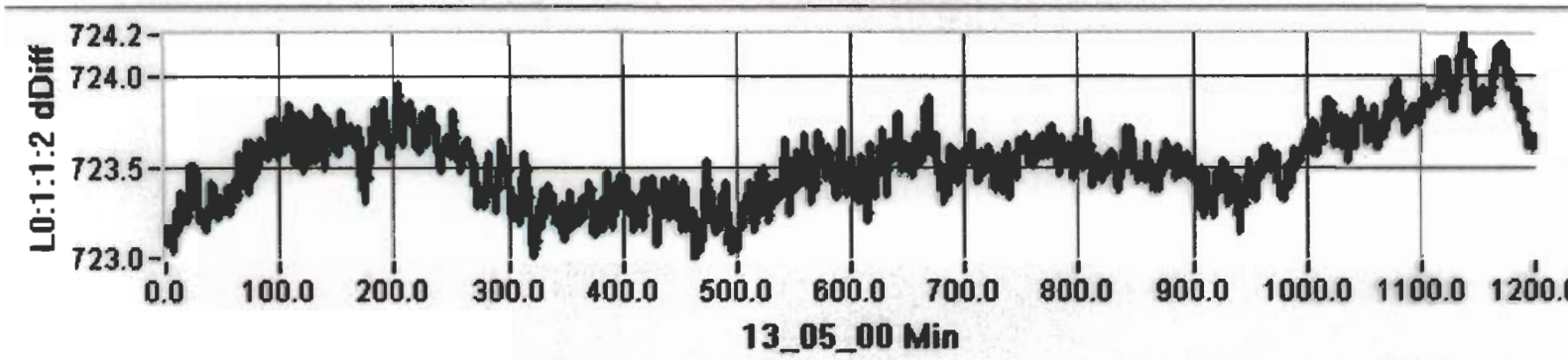
$$A = 6^{+13}_{-2} \times 10^{-8} \frac{\mu m^2}{m \cdot s}$$ ← minimum ever observed with our system (≅ Noises ?)

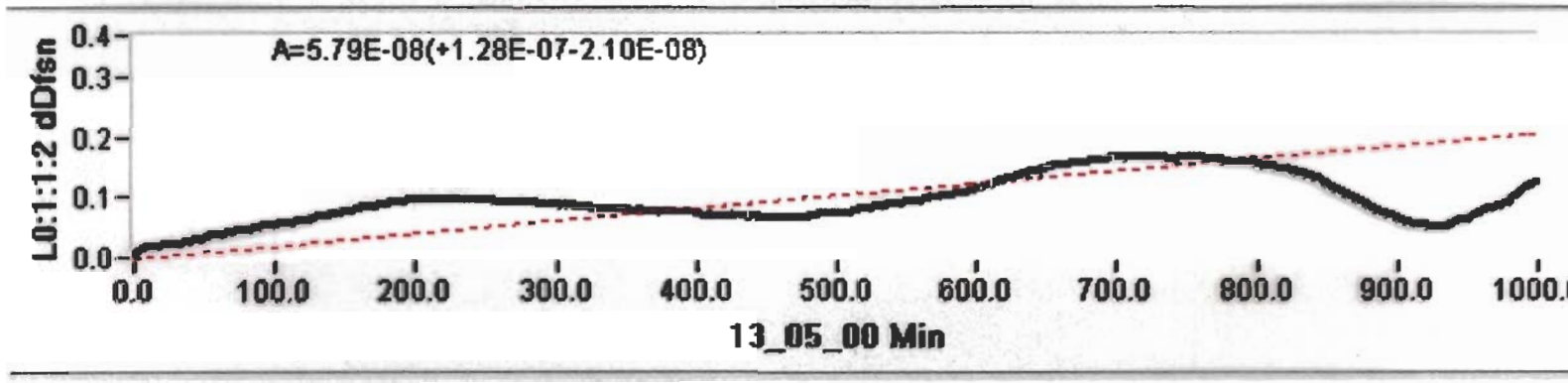


Two days record of ground motion in Aurora mine (Saturday, May 15, 2000, 4 a.m. – Sunday, May 16, 2000, 4 pm). Top plot – elevation difference of probes L0 and L7 (210 m apart) dH=L0-L7, middle – "fracture" (slope difference) of elevations of sensors ddH=(L1-L4)-(L4-L7); bottom – duffusion <ddH^2> vs time dT (in days), red line corresponds to the ATL law with A=6.34*10^-7 um^2/m/s.


L0-L1(mkm)
-105.082
-105.457
-105.831
-106.205
-106.579
-106.953
4:44
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
1100.0
1200.0
13_05_00 Min


Tm(dgC)
15.0795
15.0532
15.0269
15.0005
14.9742
4:44
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
1100.0
1200.0
13_05_00 Min


L0:1:1:2 dDiff
724.2
724.0
723.5
723.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
1100.0
1200.0
13_05_00 Min


L0:1:1:2 dDfsn
A=5.79E-08(+1.28E-07-2.10E-08)
0.4
0.3
0.2
0.1
0.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
13_05_00 Min

Conco-Western Dolomite mine

(Aurora, IL, 3 miles SW of Fermilab, 300 ft deep) "

Distance L=30-210 meter Time T=1min-1week

Diffusion Coefficient A in Units of 10^{-6} [$\mu m^2/s/m$]

Set of sensors	"whole" A	"-t^o "	"-Lin.drifts"	"-t^o-LD"
L=30 m	"quiet weekend" data, Δt^o=0.5°C			
0-1-1+2	2.0	1.6	0.66	0.58
4-5-5+6	3.0	2.88	0.25	0.24
5-6-6+7	7.6	7.56	0.31	0.26
L=60 m				
0-2-2+4	0.25	0.15	0.22	0.11
2-4-4+6	0.39	0.33	0.13	0.12
L=90 m				
1-4-4+7	0.63	0.63	0.16	0.15
< A >	2.3	1.7	0.28	0.24
	"very quiet weekend" data, Δt^o=0.1°C			
< A >	0.27	0.33	0.19	0.16
	compare with "noise" data, Δt^o=0.1°C			
< A >	0.32	0.043	0.028	0.027

"ATL-law" Diffusion Coefficient:

Part 1: FNAL Site, PW6-7

Distance L=30…180 meters

Time T=1min…3 months

$A[\mu m^2/s/m]=2\ 10^{-6}$ (average value)

$1\ 10^{-6}$ → excluding t° effects

spread (0.5….20)

Part 2: Aurora mine

Distance L=30…210 meters

Time T=1min…1 week

$A[\mu m^2/s/m]=2\ 10^{-6}$ (average value)

$0.5\ 10^{-6}$ → excluding t° effects ($_{prelim}$)

spread (0.4….10)

"ATL-law" Diffusion Coefficient

in units $A[\mu m^2/s/m], 10^{-6}$ (compendium)

	A	T	L	D_{epth}	Ref.
UNK, Protvino	100	2yr	500m	0	[1]
UNK, Protvino	100	10hrs	10m	0	[1],lab.bld.
CERN PS-pillar	2-4	2½yr	10m	10m	[1]
SPS tunnel	10-14	12yrs	2km	20m	[1], align.
LEP tunnel	7-9	9mos	1km	30m	[1], [2]
SLAC tunnel	100→10	17yrs	2mi	c&c	[1], Sery'00
SLAC tunnel	1.4	½hr	2mi	c&c	Adolphsen'98
SLAC tunnel	0.3-5	7days	2mi	c&c	Sery'2000
PEP tunnel	10	20mos	200m		[1]
Pinon Flat, CA	0.1	1yr	24m	0	[1], granite
KEK B-f.tunnel	5	96hrs	42m	12m	[1]
Esashi station	0.33	4yrs	50m	300m	[1]
Sazare mine	0.01	1wk	48m	60m	[1]
Esashi tunnel	0.006	2wks	14m	300m?	[3] drilled
Kamaishi tunnel	0.06-0.14	18days	14m	?	[3] blasted
Japan islands	35	50yrs	800km	0	[1], sea level
FNAL PW tunnel	6.4	3mos	180m	4m	cut&cover
Aurora mine (IL)	0.3	2days	210m	80m	dolomite
HERA e,p-orbit	4/15	1mo/1wk	25/50m	25m	[1]
KEK Tristan orb.	43	2days	20m	12m	[1]

[1] V.Shiltsev, Proc. IWAA'95, KEK-Proceedings 95-12, p.352 (1995)
[2] R.Pitthan, IWAA'99, SLAC-Pub-8286 (1999), dX=P*T in LEP
[3] S.Takeda, et.al, IWAA'99, KEK-Preprint 99-135 (1999)

Summary:

a) HLS noises are small <0.4 um/day
200 m long system of 6-8 HLSs with ½" ID pipes has "a response time" of 3 min.

b) slow ground motion (min-mos) consists of tides ≈20 μm at 200 m
rare remote earthquakes 10 μm (200 um absol)
mean temperature effect ≈5-10 μm/°C/100m
drifts (local T° or systematic) ≈1-3 μm/day
diffusive ground motion (= no visible reason)

c) ground motion – excluding tides + quakes/blasts – fairly well follows "the ATL law" in T. There is not enough statistics to confirm L-dependence. The diffusion coefficient in deep Aurora mine (with some 0.1 °C temperature variations) is about A=0.3 E-6 μm^2/m/s. There are indications that T° effects+systematic drifts and "bare" ATL comparably contribute (≈1:1) into such value of A. For dT°=0.5 °C the ratio is ≈10:1 with the "whole" A=2.3 E-6 μm^2/m/s.

d) diffusion in the "cut-and-cover" PW tunnel (FNAL) is many times stronger: for 3 month record <A>=6.4 E-6 μm^2/m/s and "bare" coefficient (drifts excluded) A=1.2 E-6 μm^2/m/s (dT°≈5 °C); at the time scale of 1 hour even for "quiet" days with dT°≈0.3 °C the diffusion is somewhat larger A=(10-20) E-6 μm^2/m/s.

e) diffusive ground motion is "fractal":
it has power law spectra $S \propto 1/f^2$
it has very large spread in data
it has power law statistics $\rho \propto 1/\text{Amplitude}^2$

f) there is no good model of temperature effects on a tunnel motion

g) we propose a dedicated measurements in FNAL MI tunnel with some 20 HLS probes:
MI tunnel gives unique chance to measure A in "aging" cut-and-cover tunnel;
new system with half-filled pipes will eliminate thermal water expansion effects and will have low noises $A^{noise} \approx$ 1 E-8 μm^2/m/s;
spatial (L-) dependence can be studies.