

MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
Gravitation and Cosmology Research Group  
Cambridge, Massachusetts 02139

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Facsimile Cover Sheet

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NOTES:

## DATA ACQUISITION AND ANALYSIS

### • **Prior work**

- **Prototype data analysis:**

- Periodic source of known frequency and location (Herald)

- Burst sources with generic templates (Dewey)

- Periodic sources unknown frequency assumed location (Livas, Zucker)

- Chirp sources with template (Smith)

- **Modeling:**

- Burst sensitivity with templates and crosscorrelation (Stephens)

- Stochastic background search strategies (Christensen/FLANAGAN)

- Burst coincidence sensitivity as function of detector orientation and threshold setting (Gursel and Tinto)

- Burst coincidence sensitivity with multiple detectors of different noise (Gursel and Tinto)

- Source localization vs burst detection signal to noise in a detector network (Gursel)

- **On going:**

- Prototype data analysis of apparatus generated burst statistics (Lyons)

- **Current efforts in the theoretical community**

- Analysis of compact binary chirp signals

- Dynamical information carried by chirp phase

- Optimal chirp templates

- Numerical modeling of black hole dynamics

- Stochastic background from primeaval phase transitions fluctuations

- Non-axisymmetric stellar collapse

## **EXPERIENCE WITH SEARCHES IN THE PROTOTYPES**

- **Periodic Source of Known Period and Known Position**
- **Burst Search Using Generic Templates**
- **Periodic Sources Unknown Period, Known and Unknown Position**
- **Search for Coalescing Binary Chirp**
- **Search for Periodic Signals Following SN 1987 A**

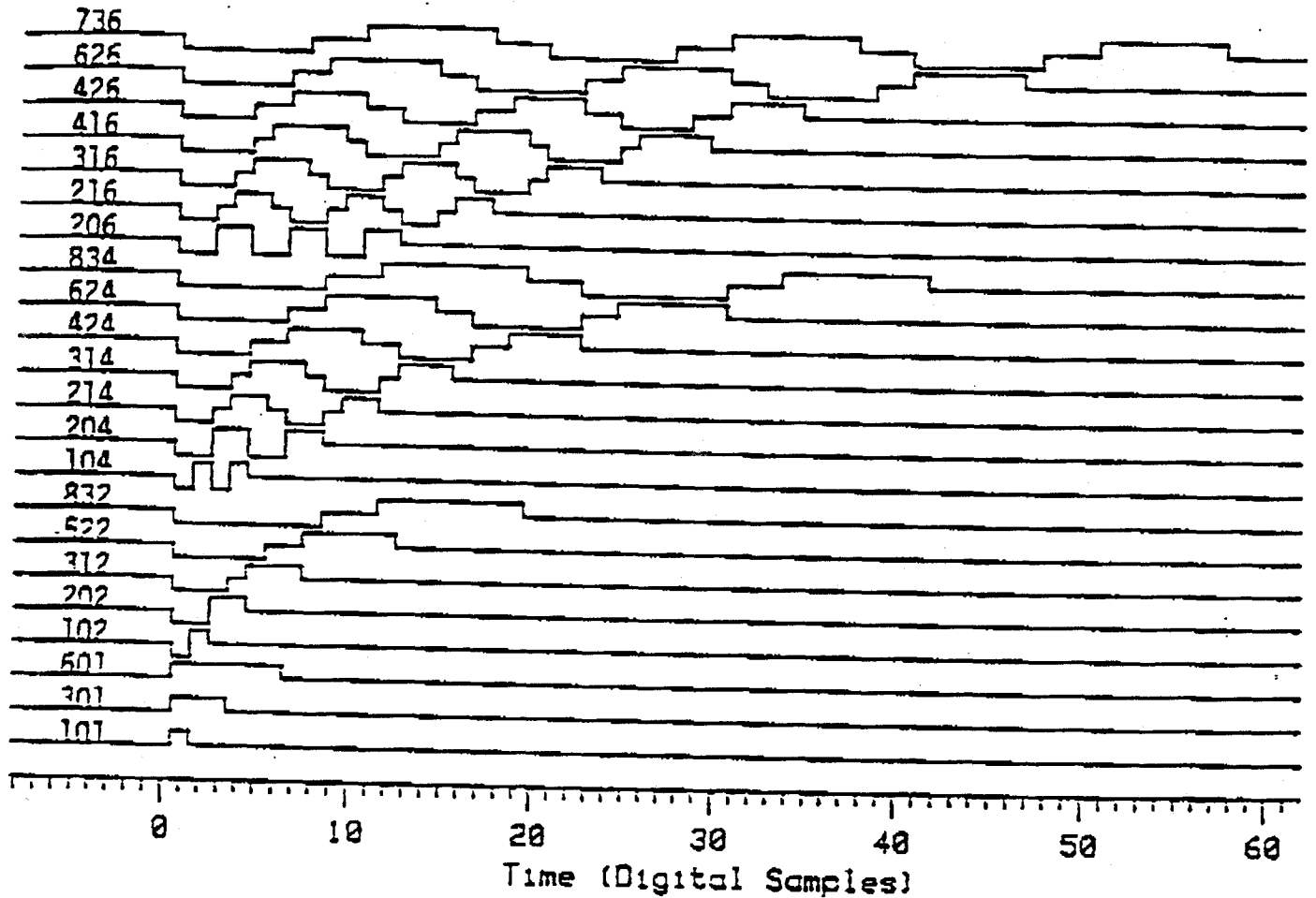
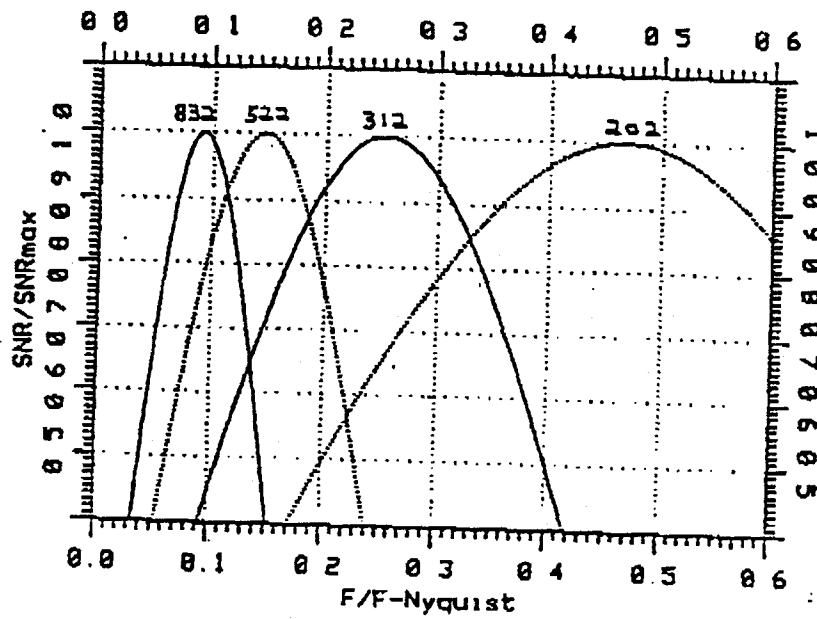
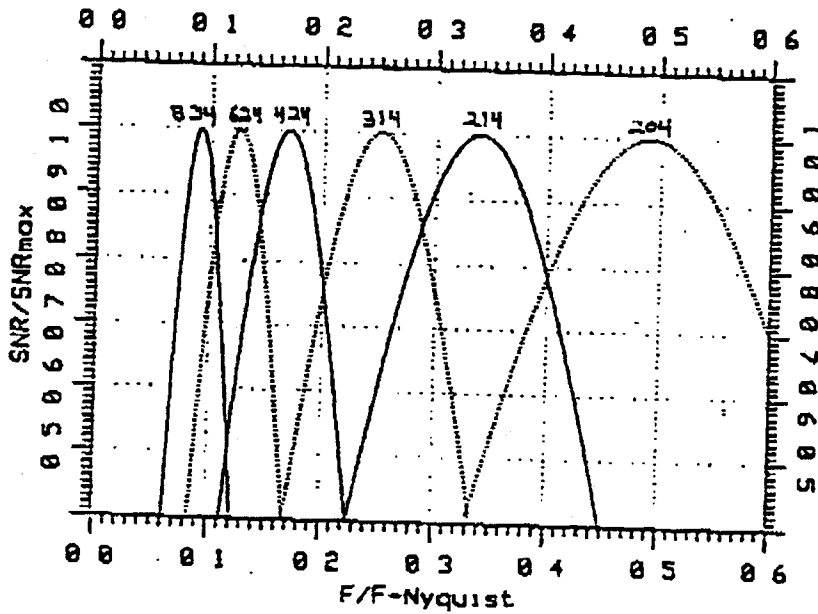


Figure 6.5 The Set of Templates and their  $N_1, N_0, NHC$  Codes

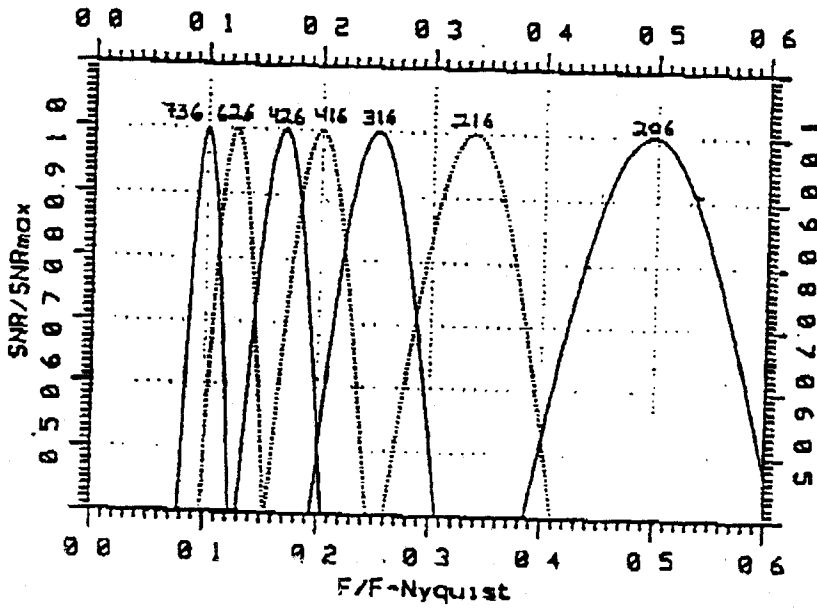
D. DEVI



NHC=2



NHC=4



NHC=6

D. DEWEY

Figure 6.6 SNR Response of the Digital Templates

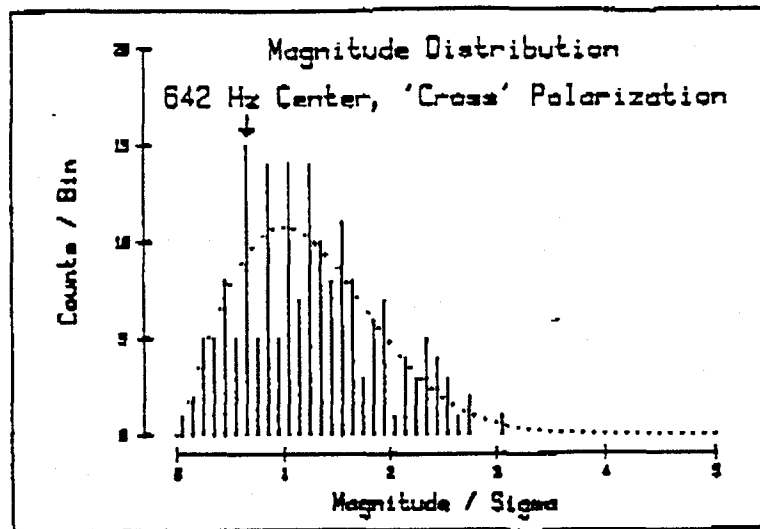


Figure I-1 The measured distribution of the magnitudes of spectral components in a 0.6 mHz wide spectrum centered at the 642 Hz millisecond pulsar frequency. The data were taken with the 40-meter facility and have been processed to extract the "cross" polarization. The dotted line is the noise distribution. The arrow indicates the bin containing the magnitude at the center frequency. (From [I-2], p. 58.)

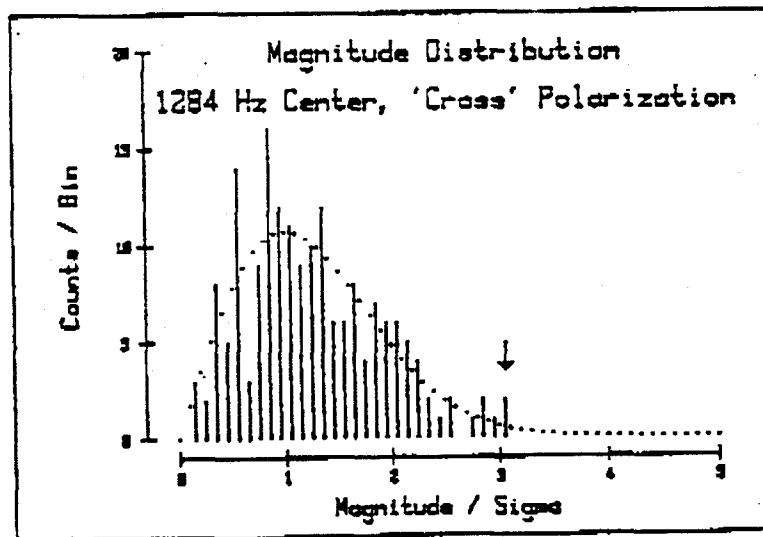


Figure I-2 The measured distribution of the magnitudes of spectral components in a 0.6 mHz wide spectrum centered at the 1284 Hz first harmonic of the millisecond pulsar frequency. The data were taken with the 40-meter facility and have been processed to extract the fixed polarization (the sensitivity to the two polarizations changes as the earth rotates). The dotted line is the noise distribution. The arrow indicates the bin containing the magnitude at the center frequency. (From [I-2], p. 58.)

frequency of 10 kHz. The maximum loss of signal to noise ratio (SNR) due to a mismatch between a real waveform and the idealized representation over this band is 75%. Each cross correlation of a finite length template with the data yields a pulse. The distribution of the amplitudes of these pulses should be a gaussian with variance determined by the

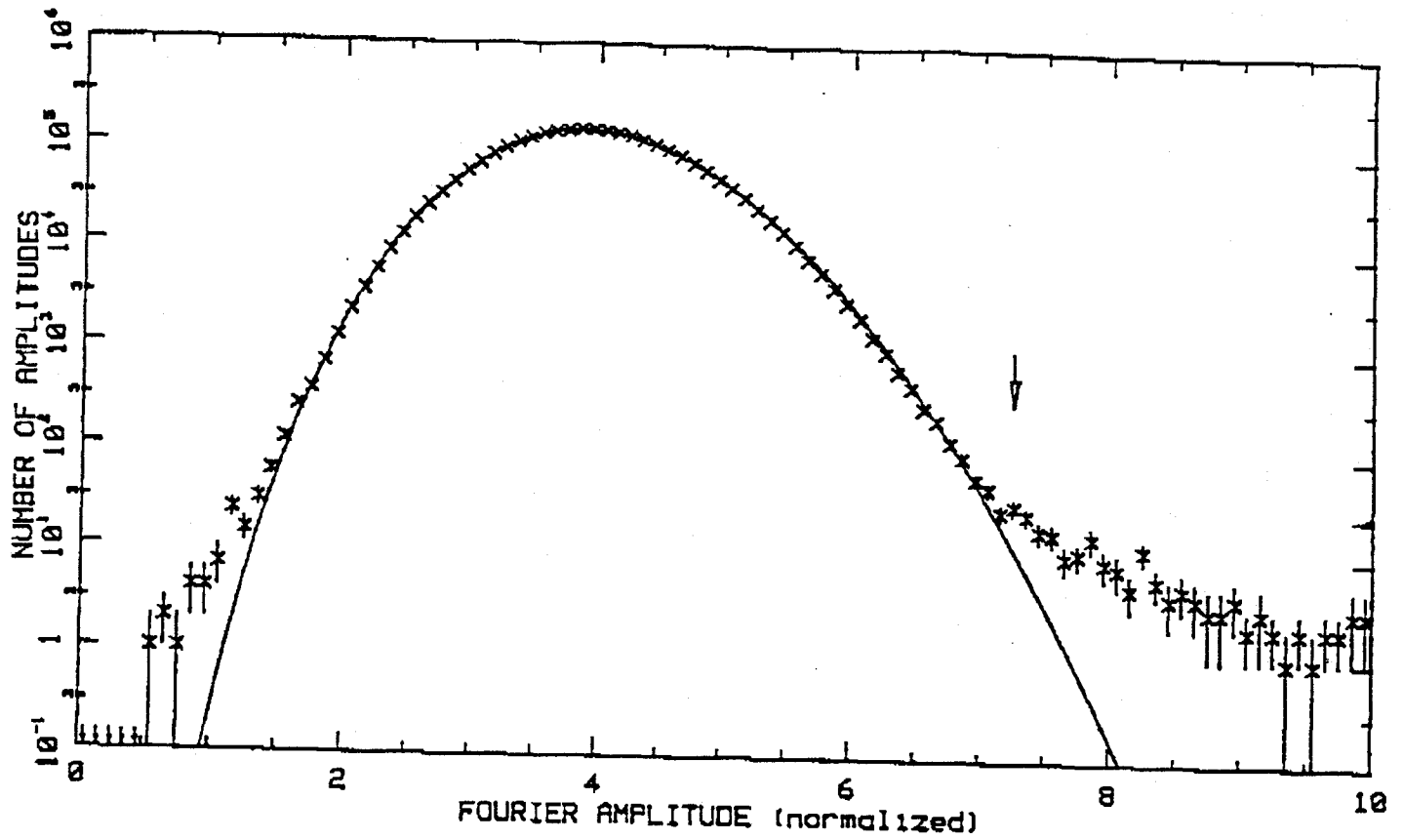


Figure 5.14  
*8-tape rms averaged power spectrum amplitude distribution.*

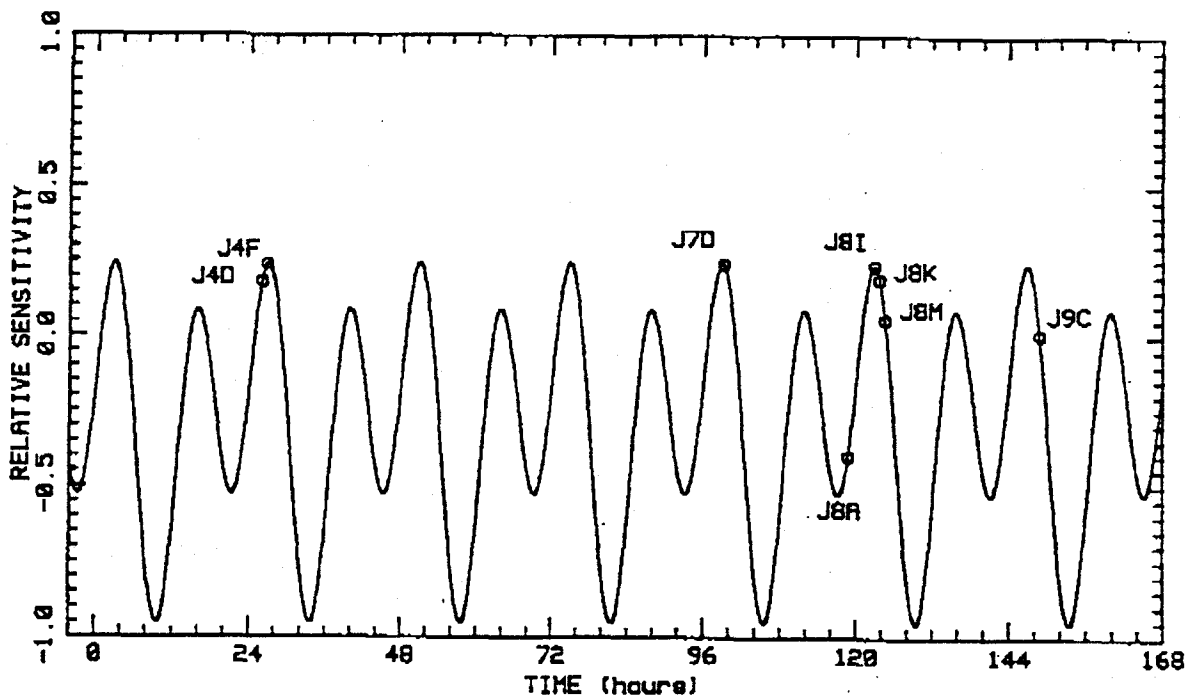


Figure 4.17a  
*AM sensitivity to a source at the galactic center: plus polarization.*

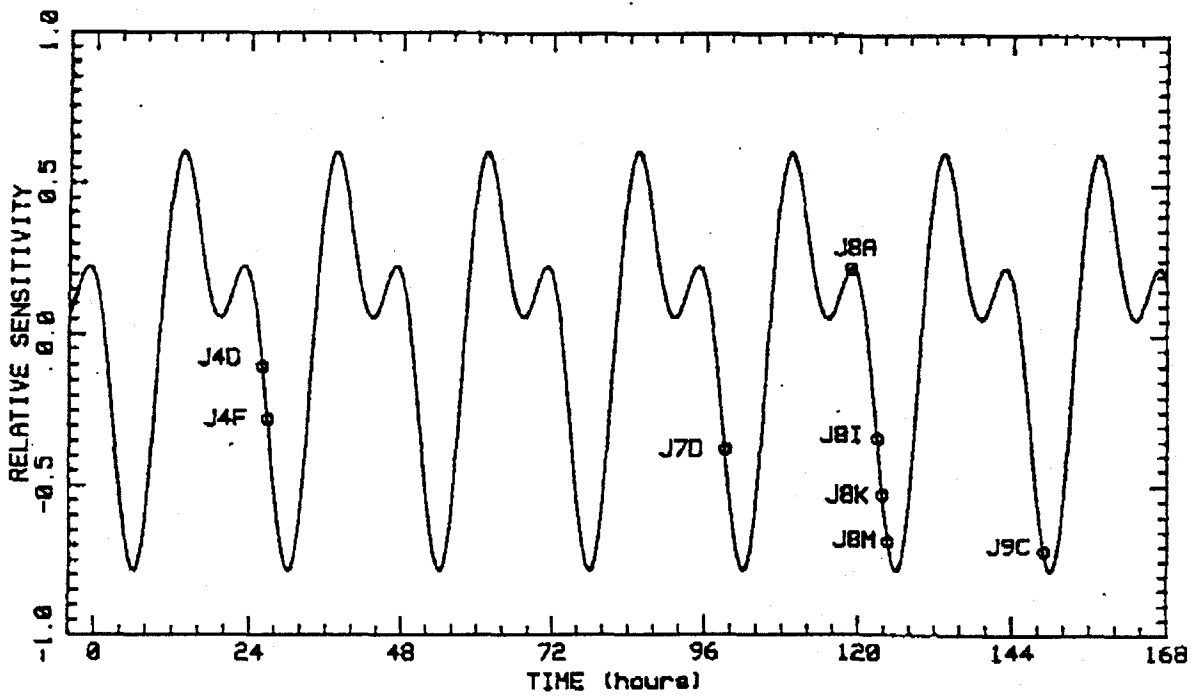


Figure 4.17b  
*AM sensitivity to a source at the galactic center: cross polarization.*



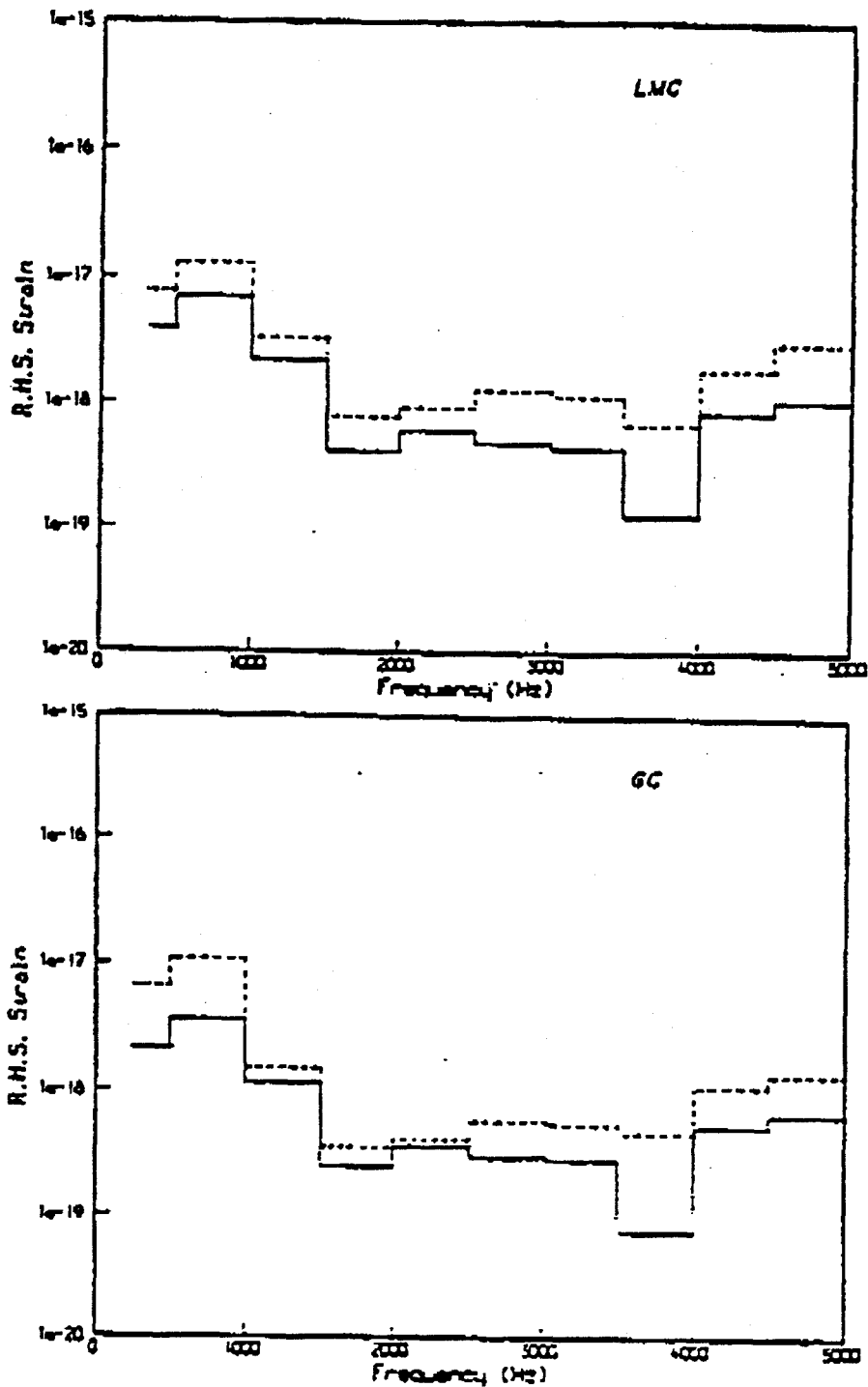


Figure 41: Composite limits on continuous gravitational waves emanating from the directions of Supernova 1987a (top) and the center of our galaxy (below). Results are shown for "+" polarization (i.e. strain aligned with celestial meridian), shown as the solid line, and "x" polarization, the broken line.

M. ZUCKER

# Things to think about in detecting periodic sources

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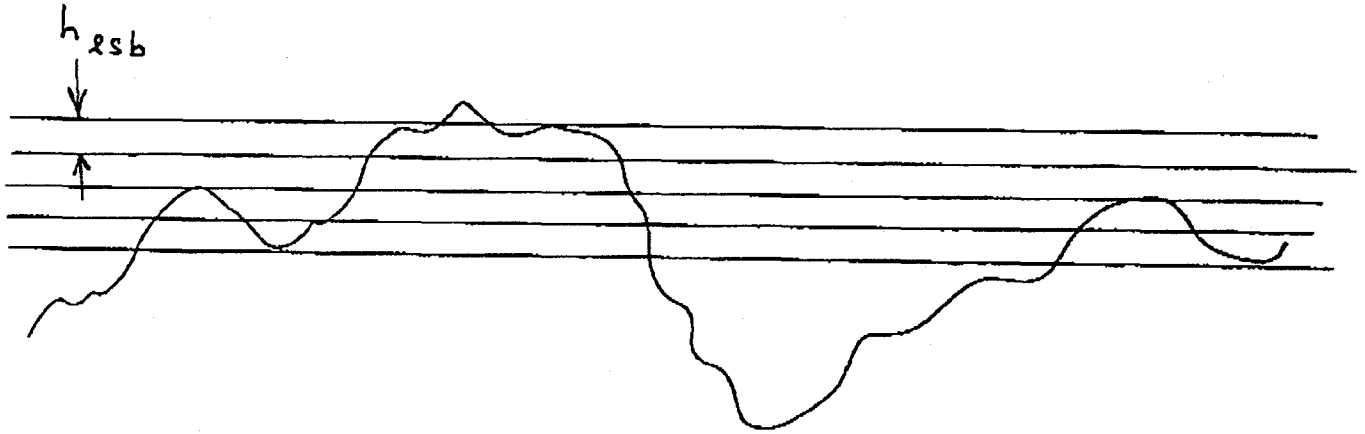
- **QUANTIZATION NOISE**
  - ›› Dynamic range and prewhitening
    - servoes
    - filters
- **LOCK LOSS AND REACQUISITION**
  - ›› Impulse removable
    - mid point averaging
  - ›› step removable
    - spline fitting
- **DISTRIBUTION OF OBSERVING TIMES**
  - ›› constraints on operations
  - ›› sidebands
    - periodic windows
    - random windows

# Quantization noise

- Dynamic range

	$h(f)$ $1/(\sqrt{\text{Hz}})$	$f$ Hz	$t_{\text{int}}$ sec	$h_{\text{rms}}$
tides		$1 - 2 \times 10^{-5}$		$1 \times 10^{-7}$
microseismic and seismic	$5 \times 10^{-11}$	0.1 - 10		
pendulum		1	10 servo damped	$1 \times 10^{-15}$
wire vertical $1 \times 10^{-3}$ cross couple		16	$1 \times 10^3$	$6 \times 10^{-20}$
wire horizontal		450	$1 \times 10^4$	$1 \times 10^{-20}$
mirror mode		16 k	$1 \times 10^2$	$7 \times 10^{-20}$
minimum initial det noise	$1 \times 10^{-23}$	150	$1 \times 10^7$	$3 \times 10^{-27}$

# Quantization noise



Variance due to quantization

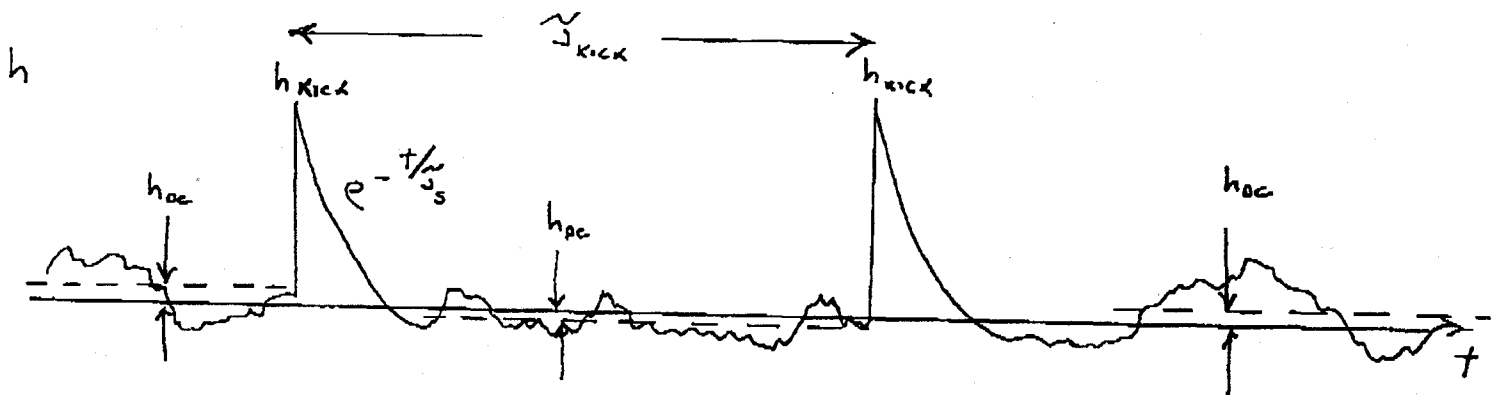
$$\sigma^2 = \frac{h(lsb)^2}{12}$$

Amplitude spectral density of quantization noise

$$h(lsb) < h(f) \sqrt{12 f(\text{sample})}$$

Depending on how well the low frequency excursions are reduced by whitening with servo control the minimum size word 16 bits (96dB) for the initial interferometer and 32 bits (193dB) for an advanced interferometer

# Lock loss and reacquisition



ASSUME POISSON DISTRIBUTION OF KICKS

$\tau_{kick}$  = AVERAGE TIME BETWEEN KICKS

$\tau_s$  = SETTLING TIME AFTER KICK

$h_{kick}$  = AVERAGE AMPLITUDE OF KICK

$h_{dc}$  = TYPICAL REACQUISITION DC VALUE

SPECTRAL DENSITY

$$h^2(f) = \frac{h_{kick}^2}{\tau_{kick}} \left( \frac{1}{\left(\frac{1}{\tau_s}\right)^2 + \omega^2} \right) \left( \frac{\omega^2}{\frac{4}{\tau_{kick}^2} + \omega^2} \right) \quad \text{FROM KICKS}$$

$$= \frac{h_{dc}^2}{\tau_{kick}} \left( \frac{1}{\frac{4}{\tau_{kick}^2} + \omega^2} \right) \quad \text{FROM RESIDUAL}$$

# Lock loss and reacquisition

## EXAMPLE

$$\begin{aligned} \text{USE } f &\sim 10^2 \text{ Hz} \\ \tilde{s}_s &\sim 10^{-3} \text{ s} \\ \tilde{s}_k &> 1 \text{ s} \end{aligned}$$

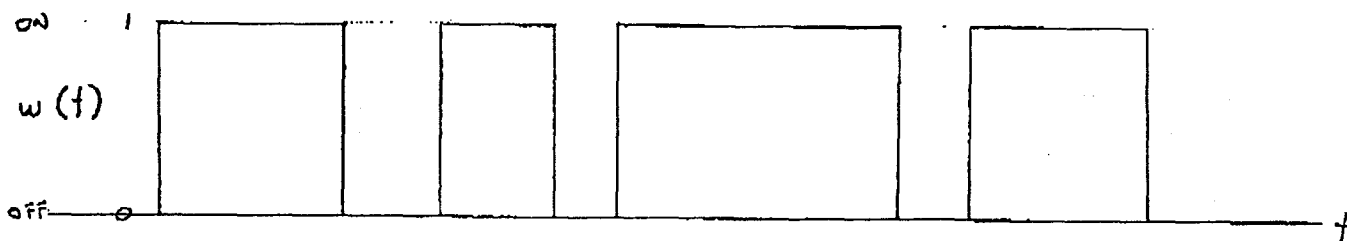
$$h_{\text{kick DC}} < h(f) \omega \tilde{s}_k^{1/2}$$

$$\text{FOR INITIAL DETECTOR } h(100 \text{ Hz}) \sim 10^{-23} \text{ } \frac{1}{\sqrt{\text{Hz}}}$$

$$\text{USE } \tilde{s}_k = 1 \text{ MIN}$$

$$h_{\text{kick DC}} < 5 \times 10^{-20}$$

# Distribution of observing times



$$h_{\text{DATA}}(t) = h(t) * w(t) \quad \text{PRODUCT IN TIME}$$

$$h_{\text{DATA}}(f) = h(f) \otimes w(f) \quad \text{CONVOLUTION IN FREQUENCY}$$

APODIZATION  
WINDOW

}

CHOSEN TO MINIMIZE LEAKAGE  
OF STRONG SPECTRAL PEAK

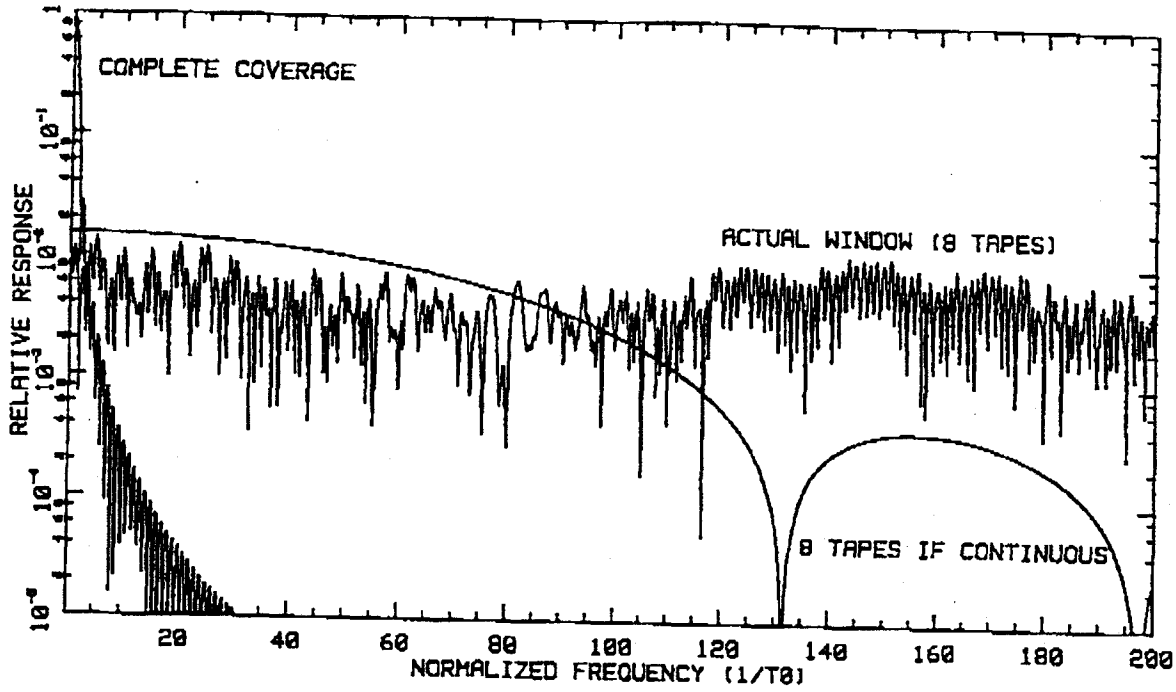


Figure 6.2a  
*Window function for the eight tapes used in the analysis.*

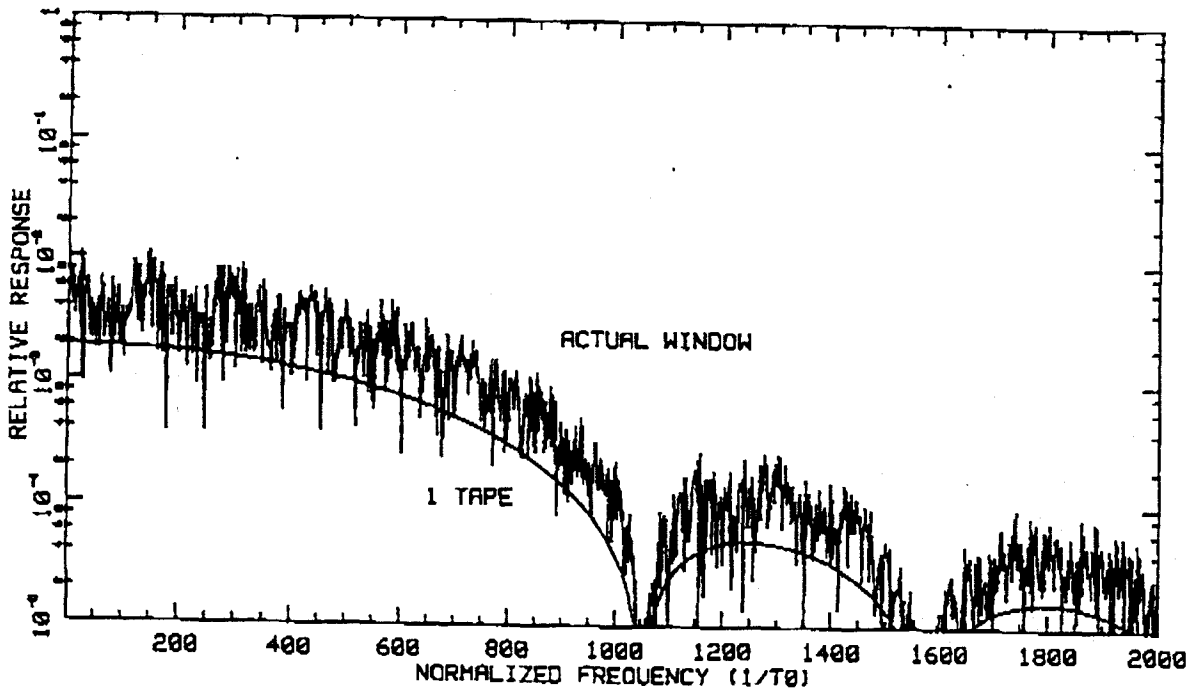


Figure 6.2b  
*Window function for the eight tapes compared with the single tape window function.*



# DATA STRUCTURES AND ANALYSIS

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- OPERATIONS
- DIAGNOSTICS
- CALIBRATION
- ENVIRONMENTAL CORRELATION
- REDUCED DATA SETS
- DETECTOR MODELS
- SOURCE MODELS
- MULTIPLE DETECTOR ANALYSIS
- DETECTION CONFIDENCE
- SOURCE STATISTICS
- PHYSICS
- ASTROPHYSICS
- CONNECTION TO OTHER FIELDS

# DATA STRUCTURES AND ANALYSIS

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- **DIAGNOSTICS**

- >> interferometer operating conditions

- state vector : binary
    - settings table: gains, time constants
    - long term avg vector: dc offsets

- >> auxiliary interferometer signals

- displacement signals: common and differential mode  
Michelson, common and differential mode cavity

- alignment signals: common and differential mode Michelson,  
common and differential mode cavity

- >> optical signals

- input light amplitude fluctuations: base band and RF
    - input light frequency fluctuations
    - input light position fluctuation vector
    - input light angle fluctuation vector
    - sideband amplitude fluctuations

# DATA STRUCTURES AND ANALYSIS

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- ›› Mechanical signals
  - Suspended mass position vectors
  - Suspended mass angular vectors
- CALIBRATION and STIMULATION
  - ›› interferometer sensitivity and spectrum
    - continuous differential cavity mode excitation
    - periodic (hourly?) spectrum
  - ›› input large amplitude intensity excitation
  - ›› input large amplitude frequency excitation
  - ›› input large amplitude beam position and angle excitation
  - ›› interferometer control loop offset step - noise spectrum
  - ›› optical component large amplitude dither vectors

# DATA STRUCTURES AND ANALYSIS

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- ENVIRONMENTAL CORRELATION

- local
- site/site

- »» TECHNIQUE

- veto
- linear regression to improve signal/noise, detection confidence

- »» PARAMETERS

- 3 axis seismic motion / building       $0.1 < f < 10 \text{ Hz}$
- 2 axis tilt / building       $f < 10 \text{ Hz}$
- 3 axis acceleration / tank       $10 < f < 1000 \text{ Hz}$
- acoustic pressure / tank       $f < 1000 \text{ Hz}$
- 3 axis magnetic fields       $f < 1000 \text{ Hz}$
- radio frequency interference / building
- cosmic ray muons / building       $t < 1 \text{ msec}$
- power line fluctuations / building

# DATA STRUCTURES AND ANALYSIS

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## >> PARAMETERS (cont)

- residual gas monitors /building /km beam tube
- \*\*molecular resonance absorption monitor /arm
- \*\*stray light monitor /km beam tube

\*\* not in current budget

## • REDUCED DATA SETS

### >> primary data/inteferometer/site

- calibrated in standard units :  $h(t)$  or  $h(f)$
- instrument signatures removed
- time tagged to microsecond
- 1 to  $4 \times 10^9$  bytes/day

### >> processed data/interferometer/site

- list of interferometer state vector and environmental vetos
- linear regression to environmental parameters
- linear regression to ancillary interferometer signals

# DATA STRUCTURES AND ANALYSIS

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- **SEARCH STRATEGIES**

- ›› **IMPERFECT FILTERS**

- prescreening if analysis is computation intensive
    - gain statistics against signal to noise

- ›› **ONLINE FILTERS**

- reduction in stored data
    - preconceived waveforms

- ›› **BURST SEARCHES**

- — threshold crossing, vetoed, event list comparisons
    - instrument and environment signatures removed, filtered cross correlation

- ›› **CHIRP SEARCHES**

- search templates (period and period derivative)
    - many detailed templates
    - $\chi^2$  minimization using model parameters

# DATA STRUCTURES AND ANALYSIS

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- **SEARCH STRATEGIES (cont)**

- » **PERIODIC SOURCES**

- all frequency, selected location
    - all frequency, all location
    - amplitude spectra over total observing time (window function)
    - average of power spectra
    - search for amplitude and frequency modulation due to motion of detector
    - how to handle wandering local oscillators
    - value of data from different interferometers at same and remote locations

- **STOCHASTIC BACKGROUND**

- frequency filtered cross correlation widely separated interferometers
  - frequency filtered cross correlation local interferometers
  - spatial anisotropy observations

# DATA STRUCTURES AND ANALYSIS

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- **DETECTION CONFIDENCE**

- ›› Uncertainty in statistics of singles detection with non Gaussian noise

- ›› Reduction to Gaussian statistics by remote coincidence

- ›› Can one use a Neyman - Pearson hypothesis test (likelihood function) with non-Gaussian noise?

- ›› How serious is the non-Gaussian noise in other than burst searches?

- ›› How elaborate does a Monte - Carlo model have to be?



# DATA STRUCTURES AND ANALYSIS

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- LIST OF CURRENT PROBLEMS
  
- 1) Benefits of linear regression to environmental and ancillary interferometer signals
  - ›› Improvement in S/N Gaussian statistics
  - ›› Improvement in detection confidence
  - ›› Models for non - Gaussian noise
  - ›› Improvement as a function of correlation coefficient and noise in correlated parameters
  
- 2) Physics/Astrophysics bounded filters
  - ›› Dynamical limits
  - ›› Conservation laws
  - ›› Astrophysical bounds

# DATA STRUCTURES AND ANALYSIS

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- 3) Trigger filters (templates)
  - ›› generic filters
  - ›› increase in signal/noise and confidence of detection with more accurate filter
  - ›› is it possible to define an optimum signal processing strategy ?????
  
- 4) Reduced Data Sets
  - ›› Define minimum pre processing to allow data to be analysed by non-experts
  - ›› Define the signals in a reduced data set
  
- 5) Advantages for a periodic search using data from two sites
  
- 6) Stochastic background and Burst Search using data from the same site

# DATA STRUCTURES AND ANALYSIS

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- 7) How to use data from multiple sites
  - >> improve detection confidence
  - >> determine position in sky
  - >> determine polarization of waves
- 8) Design the diagnostic tests

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NOTES:

ELECTRIC AND MAGNETIC FORCE  
FLUCTUATION PROJECTIONS  
MADE IN 1990 FOR INITIAL  
LIGO

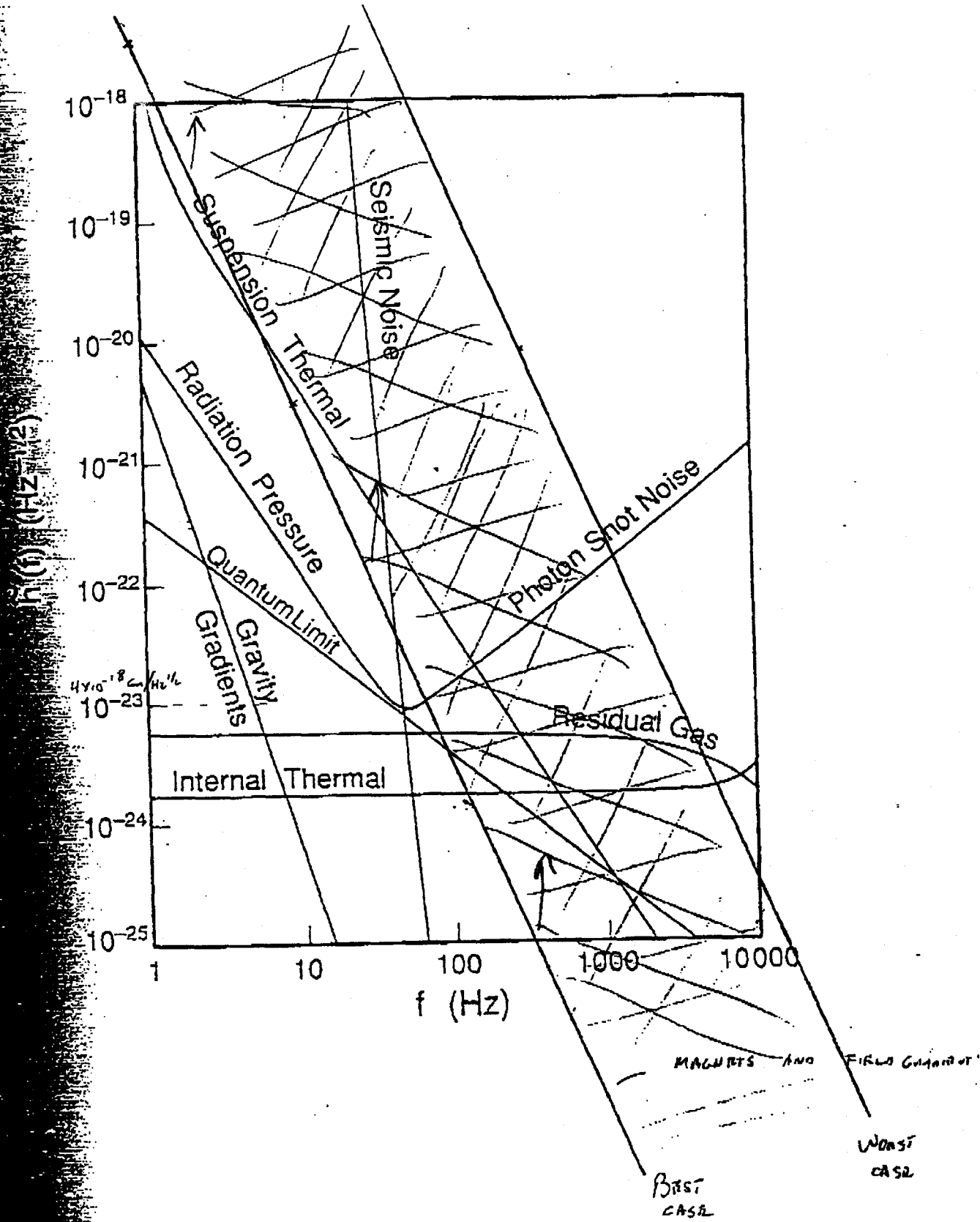


Figure III-2

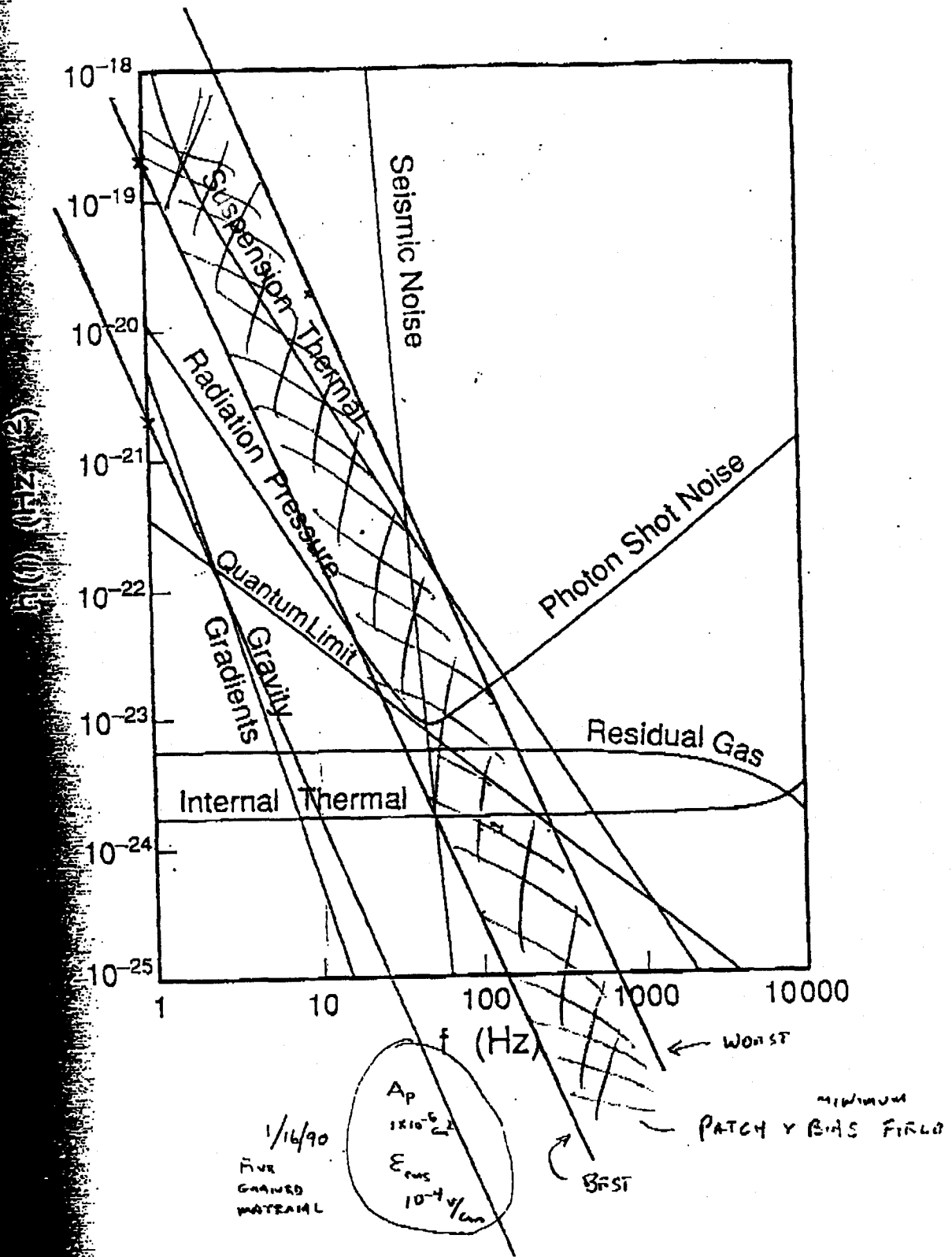


Figure III-2