Physics Studies on Accelerator Driven Sytems

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The problem of nuclear waste

- Growing stock of spent fuel, or separated plutonium and vitrified high-level waste
- Further management seems uncertain
- Main criticism against nuclear energy
- Geologic disposal an appropriate solution
  - Difficulties of siting and licensing repositories
  - Public opposition against nuclear waste
- Greater acceptability if it is possible to achieve substantial reduction in HLW
  - Minor actinides (MA) and Long lived fission products (LLFP) the main problem
  - Transmutation is a possible solution

Physics of MA transmutation

- Importance of spectrum
  - In thermal spectrum capture in the non fissile nuclides dominate which causes loss of a neutron but causes another actinide to be formed
  - In fast spectrum fission cross sections of non fissile nuclides are also significant
  - Thus fast spectrum favors transmutation
- Important Safety parameters in fast reactors
  - Delayed neutron fraction
  - Negative Doppler coefficient of reactivity
    - Significant contribution from fertile component U238
    - U238 causes more MA formation
    - Hence transmutation rates are not very high

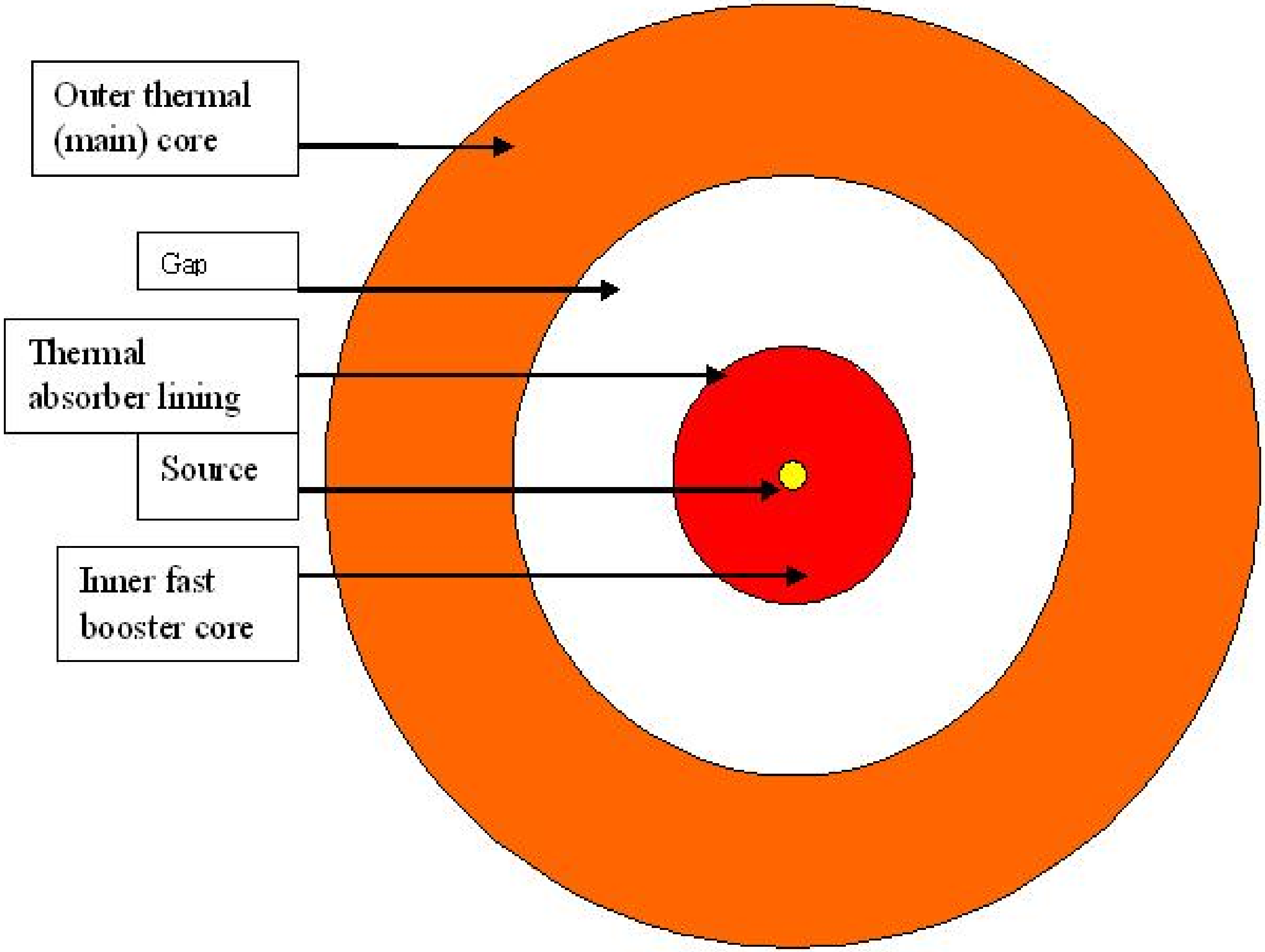
Physics of MA transmutation:

- For MA orMA+Pu fuelled critical fast reactors
    - Effective delayed neutron fraction ~ 0.15% for MA fuels
    - Doppler coefficient almost zero for pure MA fuels
    - Positive Coolant void coefficient
  - Makes such a reactor unsafe
- For MA orMA+Pu fuelled fast ADS reactors
    - These coefficients have little impact on kinetics and safety
    - Hence fast ADS is the preferred solution for MA transmutation

ADS for power production

- First proposed by Carlo Rubia et al
  - Thermal and fast energy amplifier
  - Utilises Th in a self sustaining cycle
  - Keff in the range 0.95-0.98
- Several advantages
  - Can burn Pu and MA
  - Uses more widely available Th fuel
  - Has a high degree of inherent safety
  - Produces little MAs
- Driven by 1 GeV proton beam
  - 10-15 mA accelerator
  - about one order higher than the best available

One way coupled fast-thermal ADS



One way coupled fast-thermal ADS

- **Power in ADS is inversely proportional to sub-criticality and directly proportional to neutron source strength**
- **In the control rod free concept, the operating k_{eff} is limited to the range 0.95-0.98**
- **This requires accelerator beam power of about 10-15 MW**
- **Our studies suggest the one-way coupled booster-reactor concept can reduce this requirement five fold**
  - **Inner fast core with source at centre boosts the neutron source**
  - **These neutrons leak into the outer thermal (PHWR/AHWR) core where they undergo further multiplication**

One way coupled fast-thermal ADS

- This cascade multplication gives very high energy gain
- Due to the absorber lining and the gap very few neutrons return to the booster – i.e. there is a one way-coupling between the two
- The one-way coupling ensures that the overall k_{eff} is limited to the desired value
- Consequently, accelerator power requirement for 750 MW(t) is ~ 1-2 MW

- Similar ideas have been studied in Russia
  - As an example, there is a recent proposal for a waste transmuting ADS driven by an electron accelerator

Theoretical studies on Physics of ADS

- Development of Computer codes for ADS analysis
- Theory of Reactor Noise in ADS
- Methods for computing higher alpha modes
  - Useful in deciding detector locations in pulsed neutron and noise experiments for sub-criticality measurement
- Noise simulator
  - For planning and analysis of noise experiments
- Simulation of pulsed neutron and noise experiments

Theoretical studies related to Keff measurement

- Important parameter
  - Decides power and safety
  - Hence need for measurement / monitoring
- Pulsed Neutron Experiment
  - Neutron pulse introduced periodically
  - Decay of counts vs time from pulse injection
    - Slope fit method: for determining ‘α’
    - Area ratio method: for detrmining ρ/β
- Source jerk method
  - Source switched off repeatedly after long steady operation
    - Decay of flux observed as a function of time: gives ‘α’
    - Ratio of steady flux with source on and sorce off: gives ρ/β

Theoretical studies related to Keff measurement

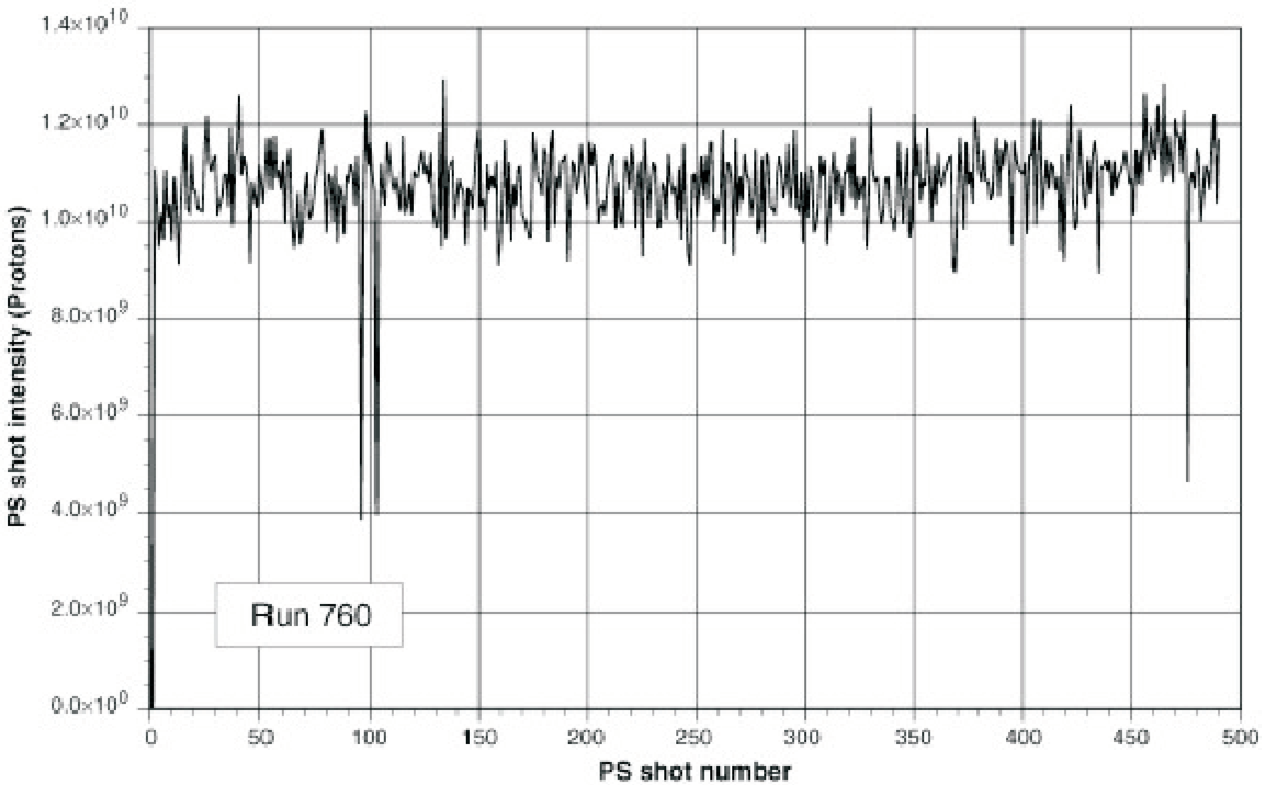
- Noise methods
  - Do not require interruption of reactor operation
    - Do not require pulsing or switching off
    - Can also work if source is pulsed
  - Possible Methods
    - Feynman alpha
    - Rossi alpha
    - Auto and cross correlation
    - Psd and cpsd methods
- Work on these methods by various groups at Muse, Yalina and Kuca facilities

Reactor Noise in ADS

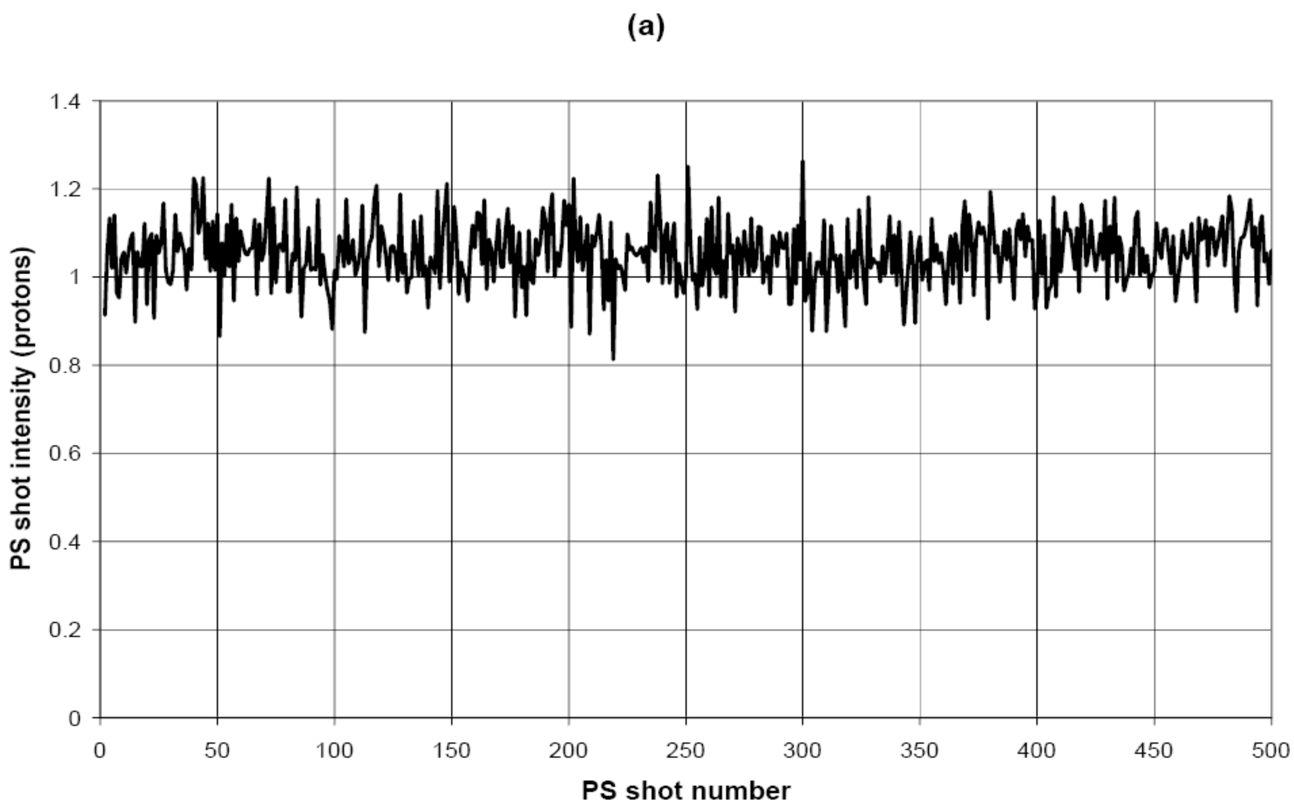
- Radioactive sources as Poisson sources
  - Large number of radioactive atoms
  - Relatively small number decay
- Accelerator sources
  - Pulsing
  - Cw accelerators
  - Fluctuations in intensity
    - Typically about 2%
    - For Poisson source of 1e8 strength should be only 0.01%
  - Correlations in these fluctuations?
- Periodically Pulsed sources as Poisson sources?
  - Contradictions in Munoz-Cobo's formulae

Example of measured proton beam current

A. Abanades et al.: TARC experiment, Nucl. Instr. Methods, A478, 577(2002)



Uncorrelated Gaussian process
(Simulation)



Reactor Noise in ADS

- First papers considering the non Poisson character of source
  - S.B.Degweker, ANE 30,223 (2003) ANE 27,1257 (2000)
  - Derivation of
    - Feynman alpha (variance/mean)
    - Rossi alpha
    - Auto correlation function
    - Power spectral density
    - Two modes of counting
    - Space energy dependence
    - Large pulsing frequency limit
  - Main results
    - Noise strength changes
    - Noise spectrum is unaltered in high pulsing frequency limit
    - Both are altered for frequencies comparable to alpha
  - Finding increasing acceptance

Reactor Noise in ADS

Finite pulse widths

- Rectangular and Gaussian pulse shapes
- Doubly stochastic Poisson point process
  - Use Bartlette formula but treat the ion current as an exponentially correlated Gaussian process
- Derivation of
  - Feynman alpha (variance/mean)
  - Rossi alpha
  - Auto & cross correlation functions
  - Auto & Cross Power spectral densities

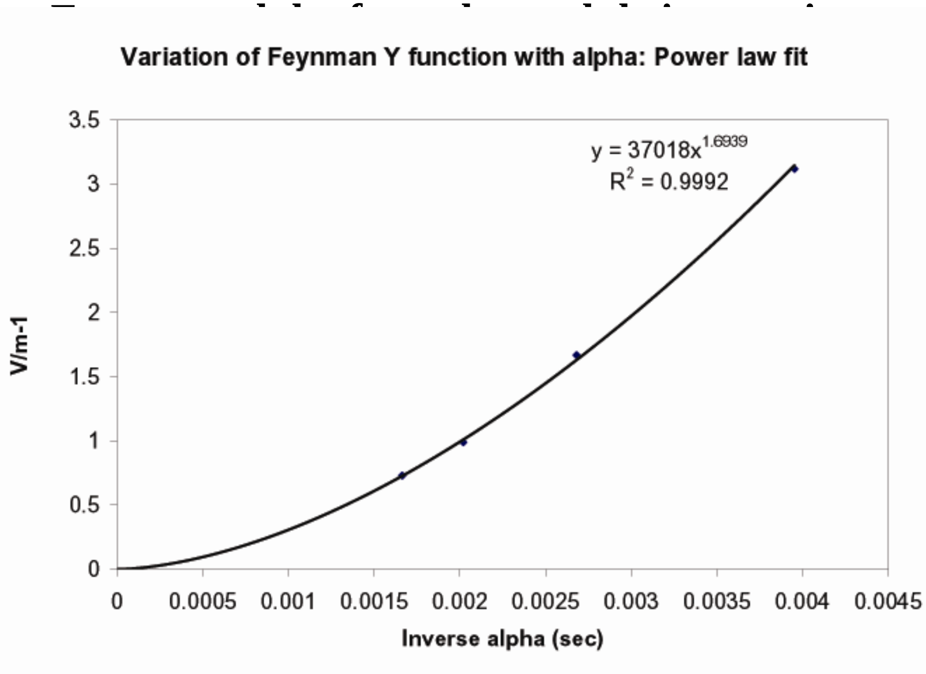
- Delayed neutrons
- Most general problem
  - Langevin approach

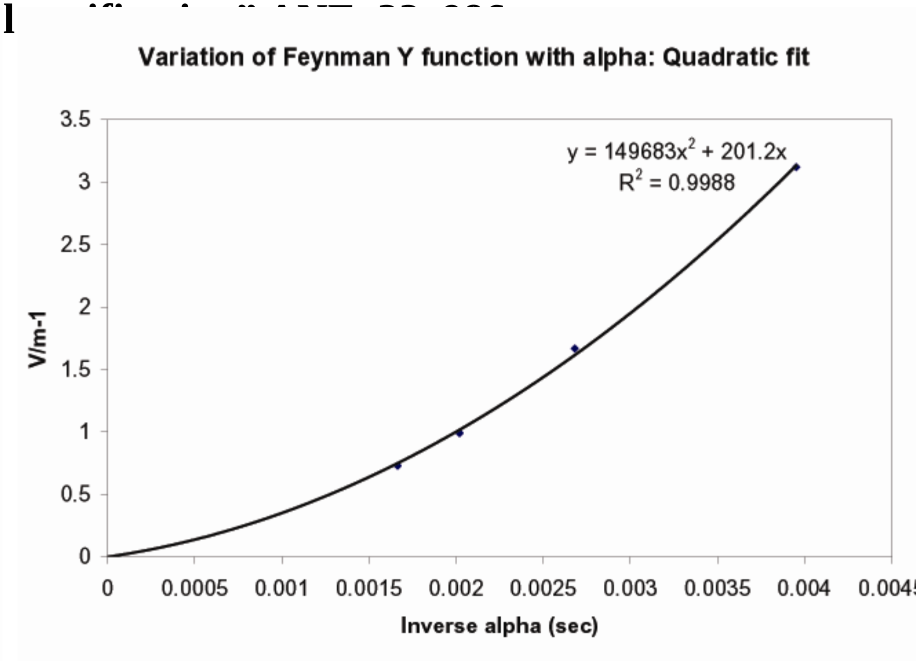
Another Example *[Y.S.Rana, S.B.Degweker, Nucl. Sci. Eng. 162, 117 (2009)]*

Variation of v/m with inverse of the decay constant

points are based on the experimental results presented in-

Pazsit I., Y. Kitamura, J. Wright, T. Misawa (2005) “Calculation of the pulsed





- **While both fits are equally good, the power obtained is not 2 as is expected on the assumption of a Poisson source**
- **The quadratic fit passes through the origin and the linear term indicates a non Poisson source contribution**

Summary of Studies on Noise in ADS

- Reactor Noise analysis is an important tool for measurement of Reactor Physics parameters and for monitoring and surveillance for online fault detection and diagnosis
- Similar techniques are likely to prove useful in ADS
- Reactor noise in ADS is different from ordinary reactors due to the different statistical characteristics of the driving source and requires a new theory.
- The difference is likely to be important in the interpretation of noise based measurement / monitoring systems
- Such a theory has been worked out in BARC and is now accepted as *the* theory of Reactor Noise in ADS

The modified power iteration method for higher mode generation

Scheme for sub-critical reactor

Let us assume that the reactor being modeled is subcritical so that all alpha eigenvalues are negative. The dominant values are those with smallest magnitude (or slowest decay). With *A* and *F* representing removal and fission matrices, the alpha eigenvalue equation

$$[A - F]\phi = -\frac{\alpha}{v}\phi$$

is rewritten in the form

$$[A - F]^{-1} v^{-1} \phi = -(\frac{1}{\alpha})\phi$$

Thus, it is an eigenvalue problem for the matrix $M = [A - F]^{-1} v^{-1}$

The eigenvalues of M are (-1/α) which are all positive and largest values of (-1/α) form the dominant modes to be computed. These are computed using the sub-space iteration method.

The modified power iteration method for higher mode generation

This requires a capability to evaluate product of M with any given flux guess vector x of size NxG. This can be achieved by solving an external source problem in multiplying medium.

M is a square matrix of order (NGxNG), where N is number of mesh points and G is number of energy groups.

In practical 3-D problems of multigroup diffusion equation, N.G is very large. It is difficult to explicitly form the matrix M by inversion. Moreover, M will be a full matrix and its storage is difficult.

On the other hand, while solving a source problem to find Mx, the sparsity of A and F is exploited. Thus effect of M on a vector is found without explicitly forming M.

The modified power iteration method for higher mode generation

Extension for Super-critical reactor

The above scheme cannot be used straightaway for supercritical reactors for two reasons.

Firstly, at least one of the dominant alpha eigenvalues will be positive while many others will be large negative. The positive value need not be larger in magnitude than all the negative eigenvalues. Hence, the dominant modes required do not have largest/smallest magnitude. Therefore, neither power iteration nor any of the three methods can be used to find the dominant modes.

Secondly, the external source problem in multiplying medium has no solution if the medium is super-critical.

This problem of super criticality is avoided by subtracting (β/ v)Φ from both sides of the eigenvalue equation where β is a suitable real constant.

This gives:

$$[-(A+\frac{\beta}{v})\phi+F\phi]=\frac{(\alpha-\beta)}{v}\phi$$

By choosing a suitable value of β one can assure the sub-criticality of reactor.

Thus, $\alpha-\beta$ is negative for all modes.

Solution of eigenvalue equation then gives $\alpha-\beta$ as eigen values.

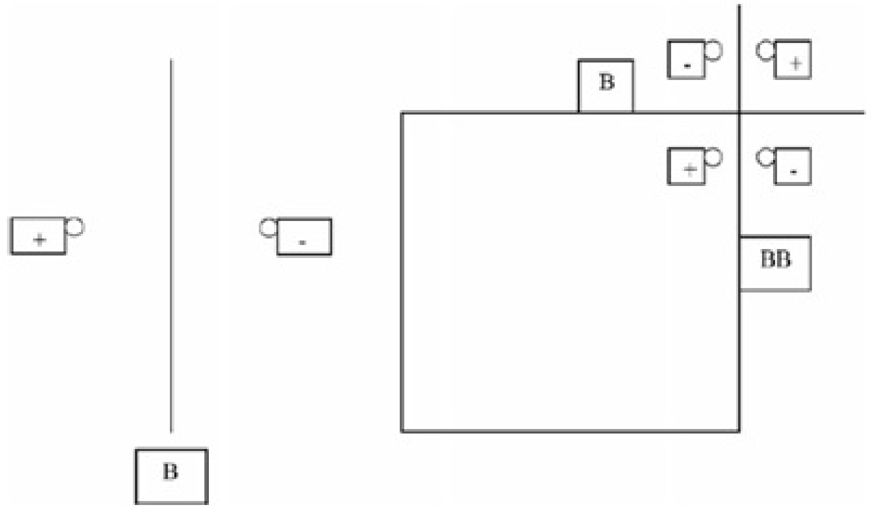
From this α eigen values can be calculated by adding β.

Noise simulator

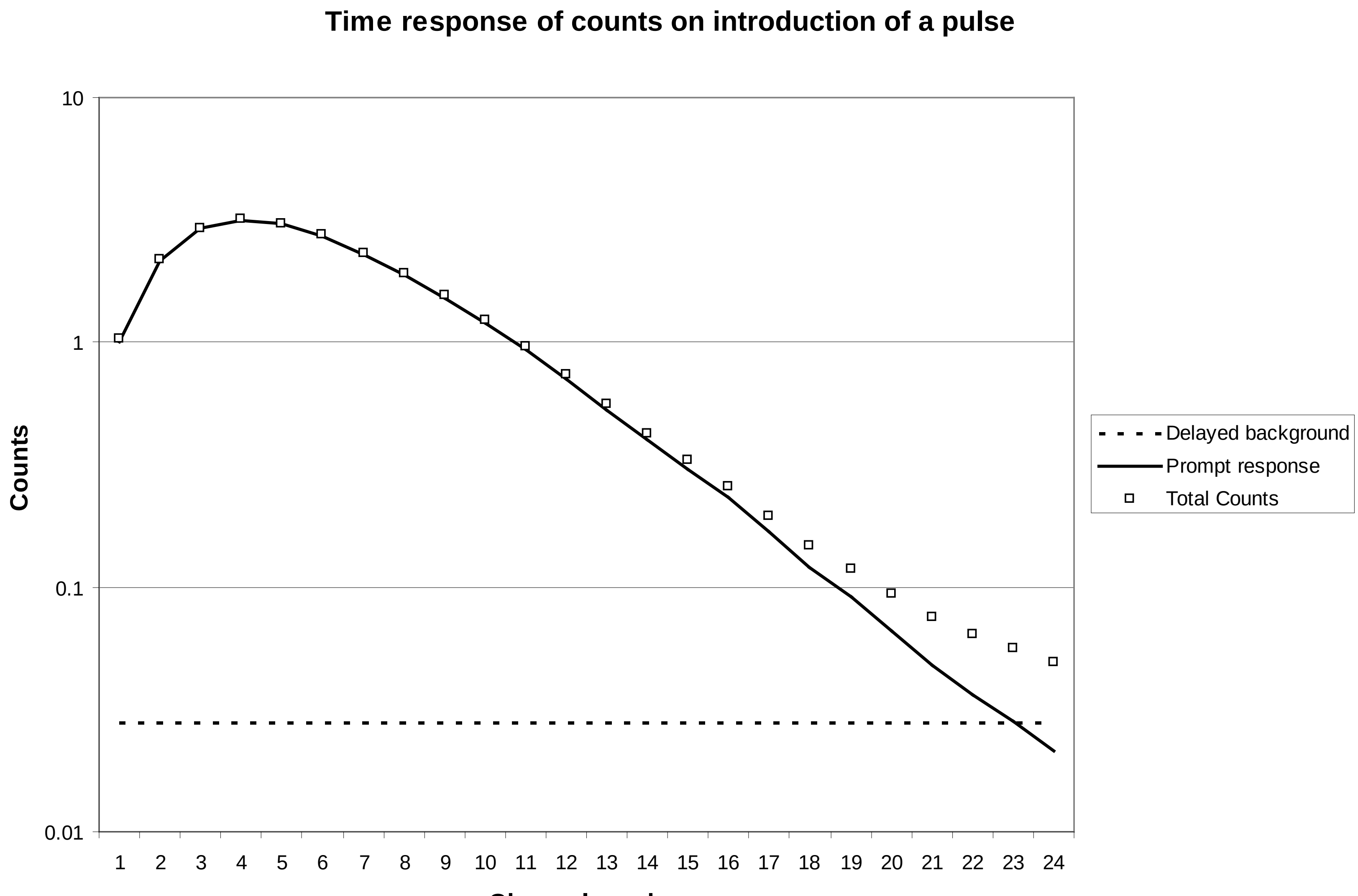
- To study various factors affecting measurements
  - space dependent effects; modal contamination
  - Statistical errors
  - Dead time errors
  - Delayed neutron effects
- Conventional Monte Carlo codes
  - Non-analogue features built in
  - Analogue simulation is time consuming
- Analogue 'diffusion theory' Monte Carlo simulator
  - Derivation of few group diffusion kernels
    - Analytical kernels for finite rectangular geometries
      - Now generalised to include cylindrical geometry, multi media
    - Finite difference kernels for more general geometries
- Transport theory based noise simulator

Infinite medium kernel and method of images for finite media

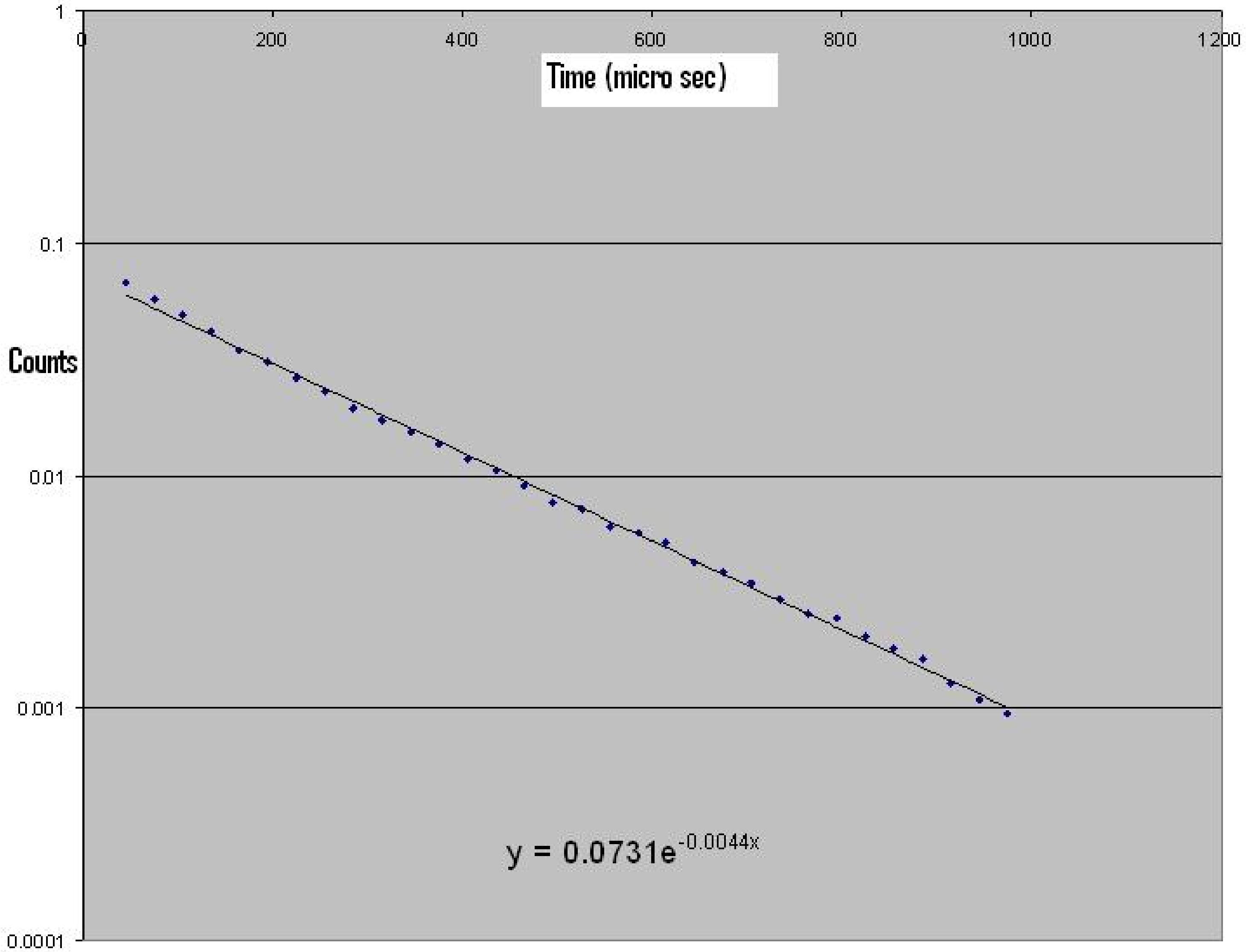
$$P(\vec{r},t) = \frac{1}{l(4\pi Dvt)^{3/2}}\left[\exp\left(-\frac{|\mathbf{r}-\mathbf{r}'|^2}{4Dvt}\right) - \exp\left(-\frac{|\mathbf{r}-\mathbf{r}''|^2}{4Dvt}\right)\right]\exp(-t/l)$$



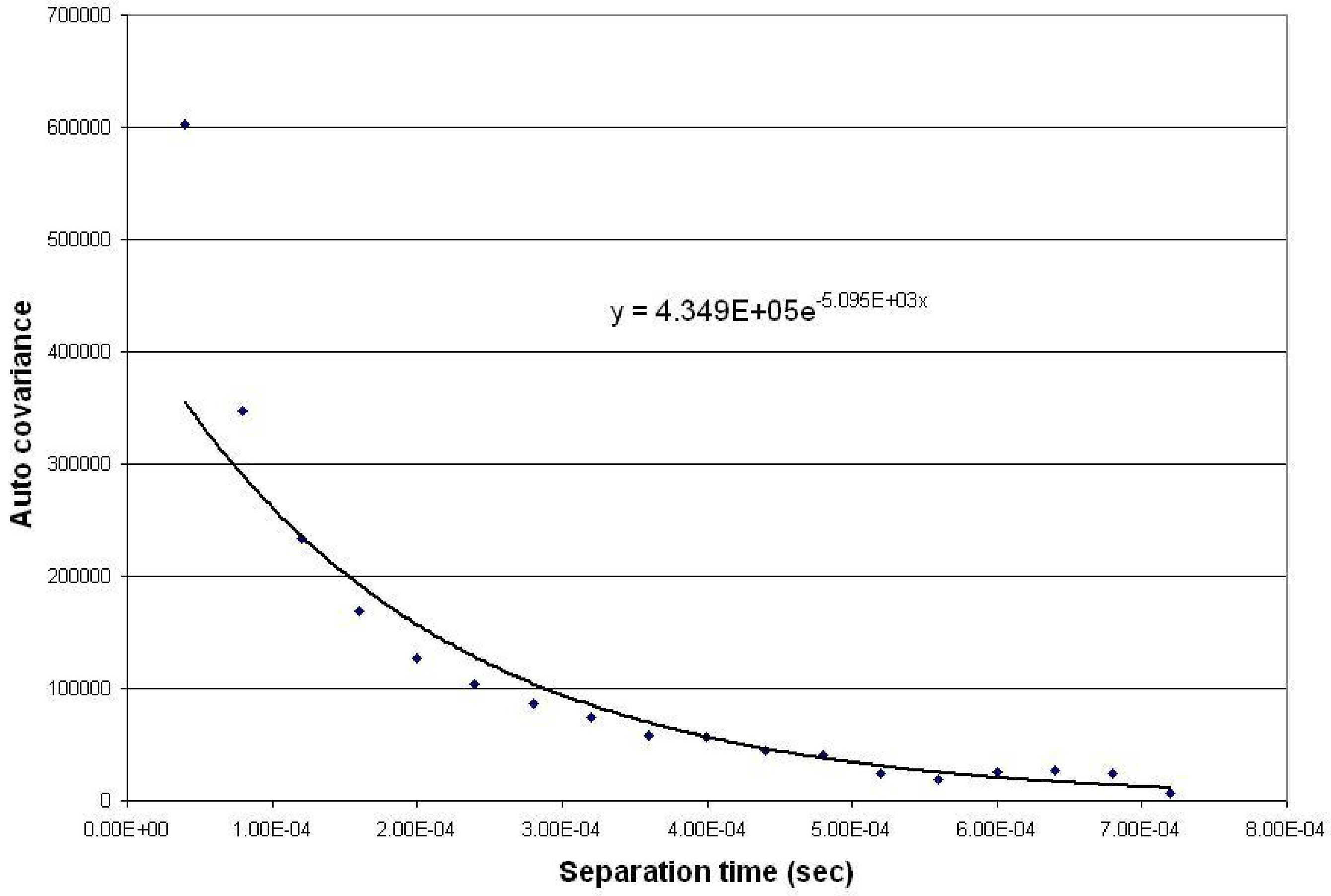
Pulsed neutron experiment simulation
Detector located in reflector



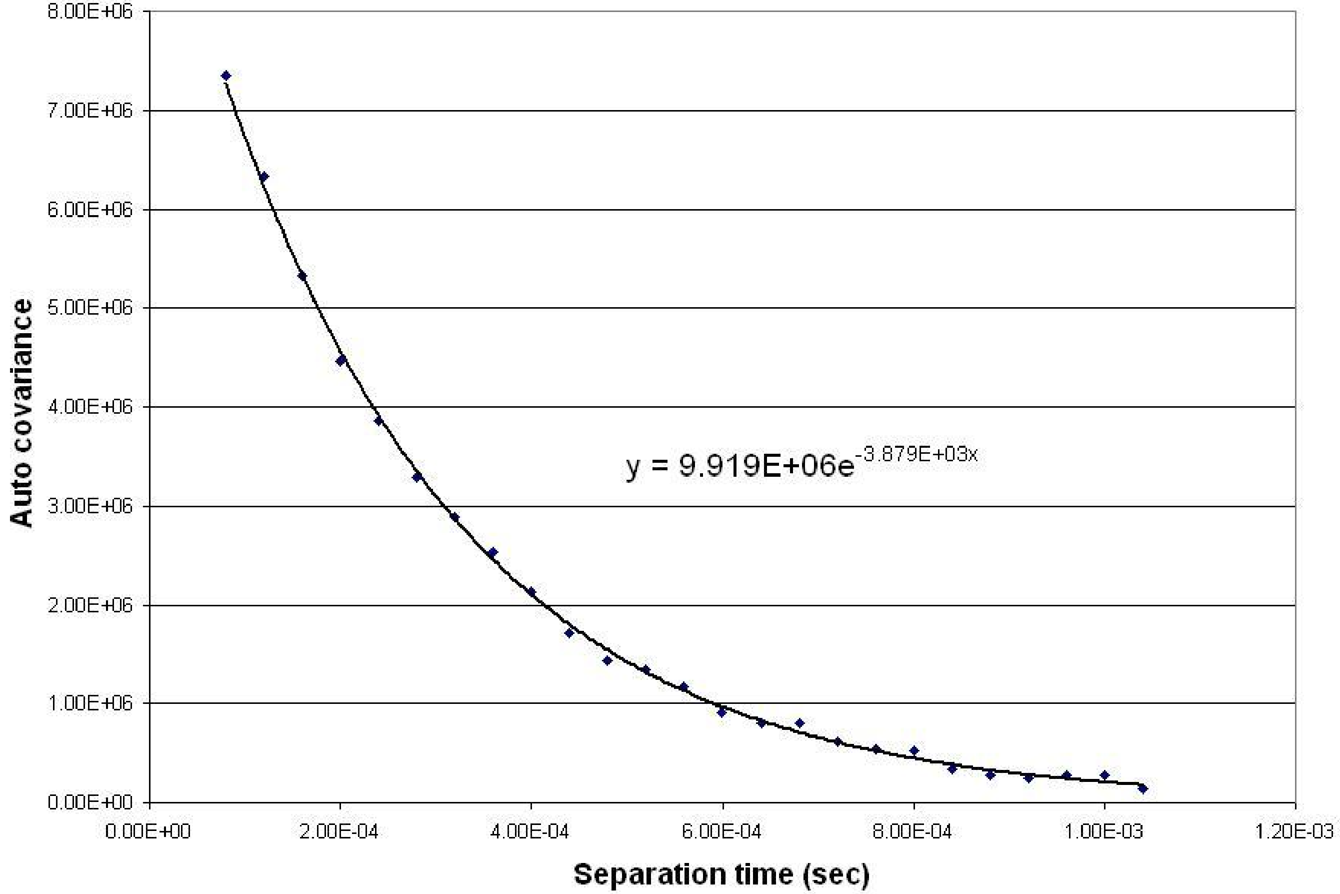
Pulsed neutron experiment simulation Detector located at zeros of modes



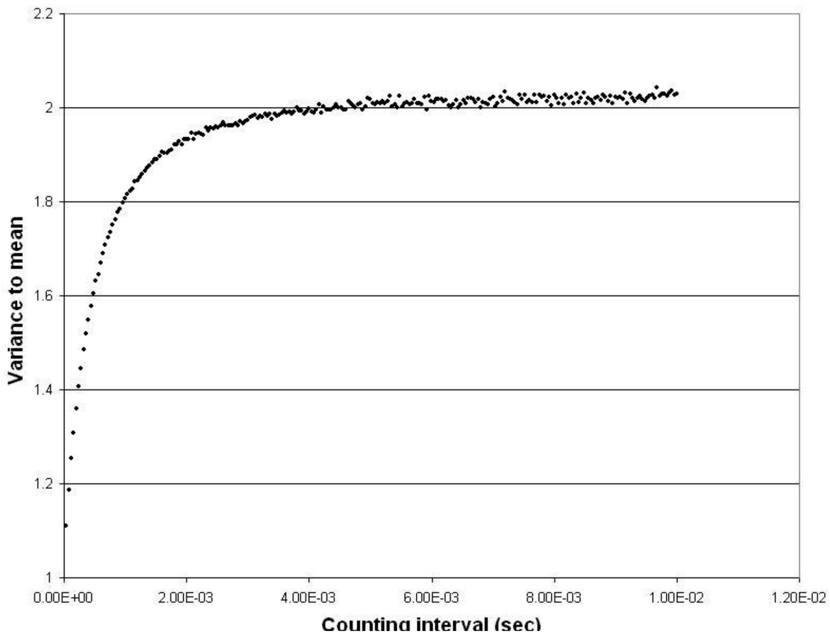
ACF Results from noise simulator with detector located anywhere

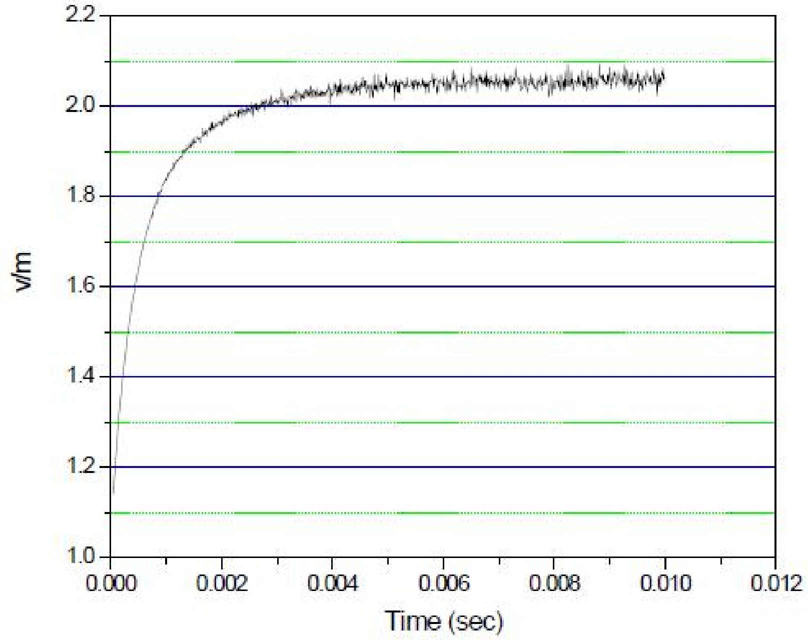


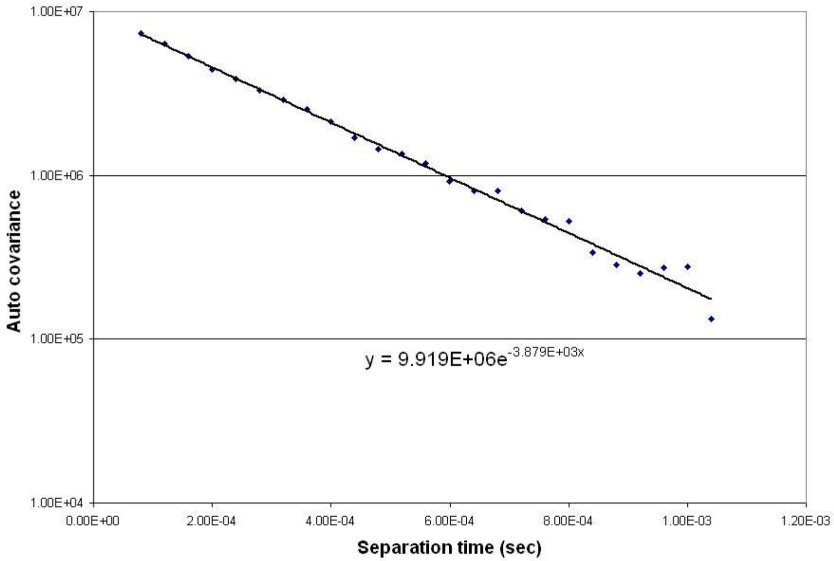
ACF Results from noise simulator with detector located at zero of higher modes

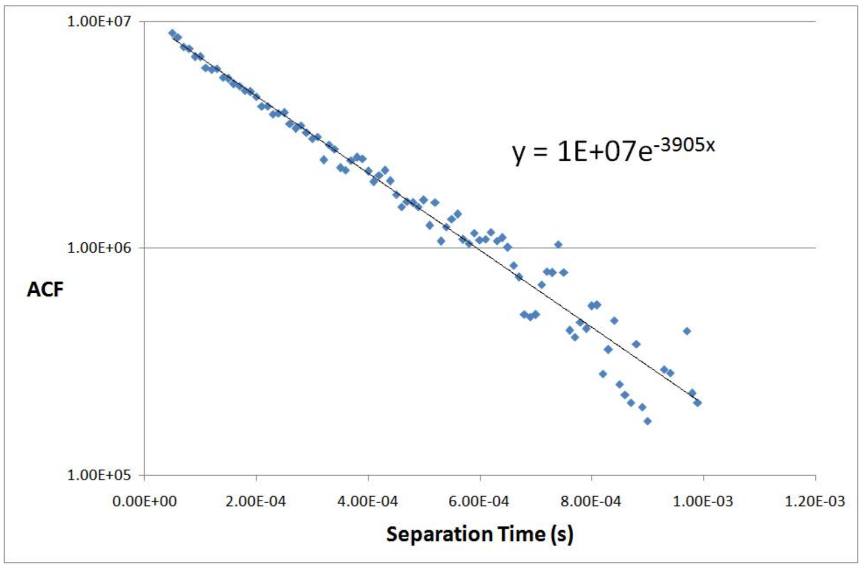


V/m and ACF: Analytical vs finite difference









THANK YOU