Pico-Precision Displacement Sensor using Digital Image Analysis

Jiro Murata

Department of Physics, Rikkyo University

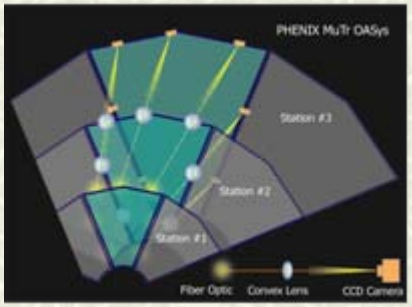
3-34-1 Nishi-Ikebukuro, Tokyo, 171-8501, JAPAN

jiro@rikkyo.ac.jp

IEEE Nuclear Science Symposium, Puerto Rico, 2005

Contents

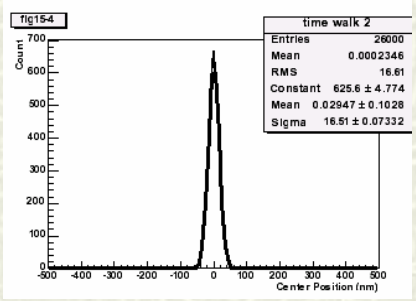
1



Initial System

Optical Alignment System for PHENIX Muon Tracking Chamber
System Resolution = micron scale

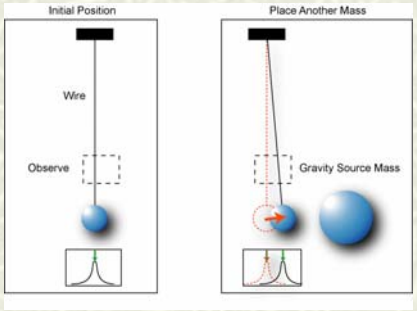
2



Specialized

Dedicated Position Sensor
System Resolution = pico scale

3

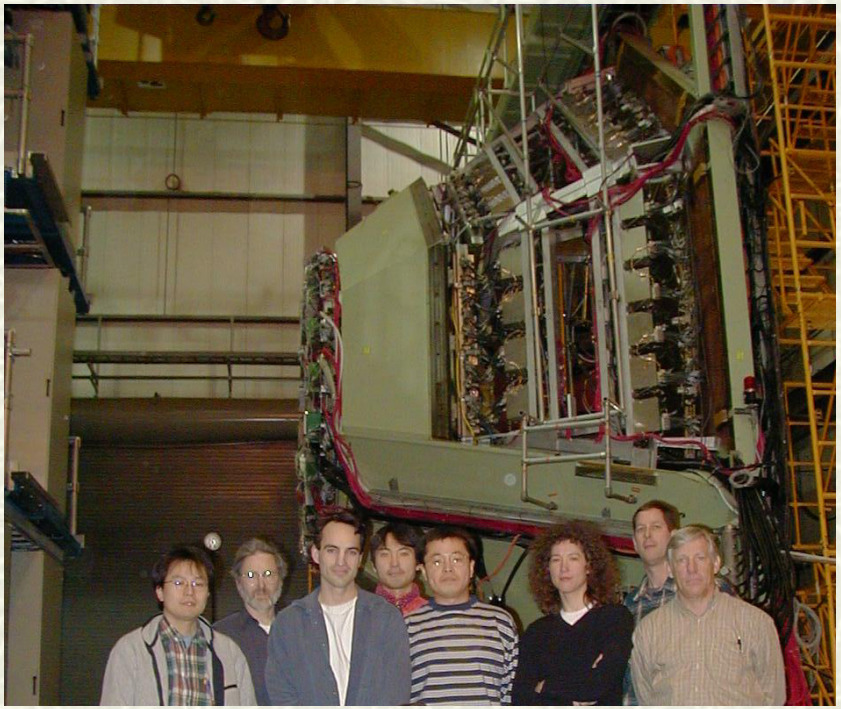


Application

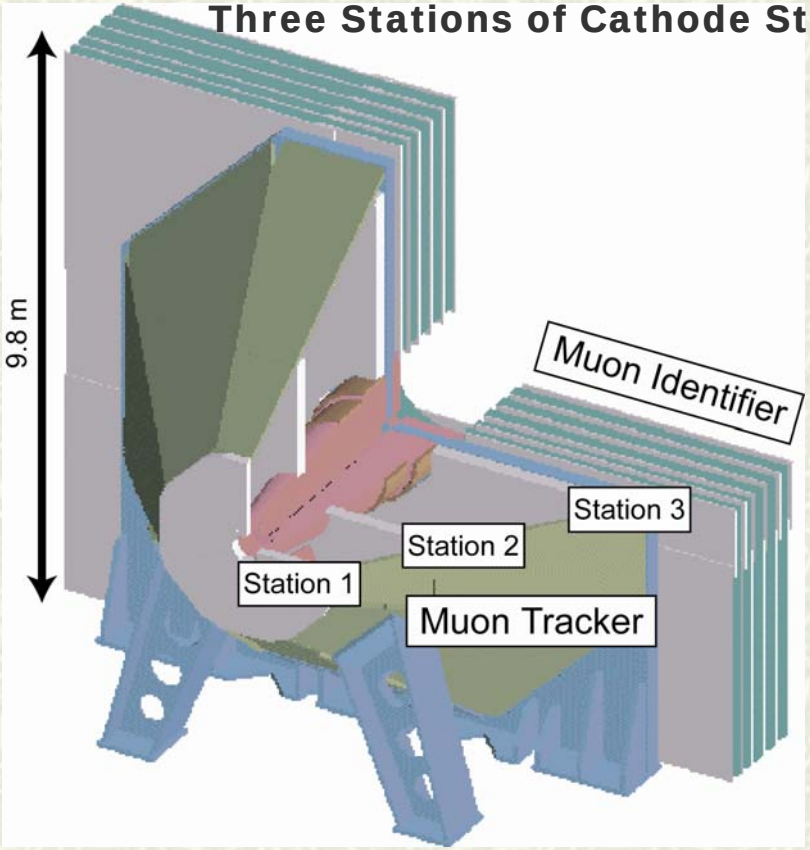
Application to Short Range Gravity Experiment
Test of Newton's Law in mm scale

Starting Point: PHENIX Alignment System

Muon Tracking Chamber of PHENIX, RHIC, Brookhaven



Three Stations of Cathode Strip Chambers

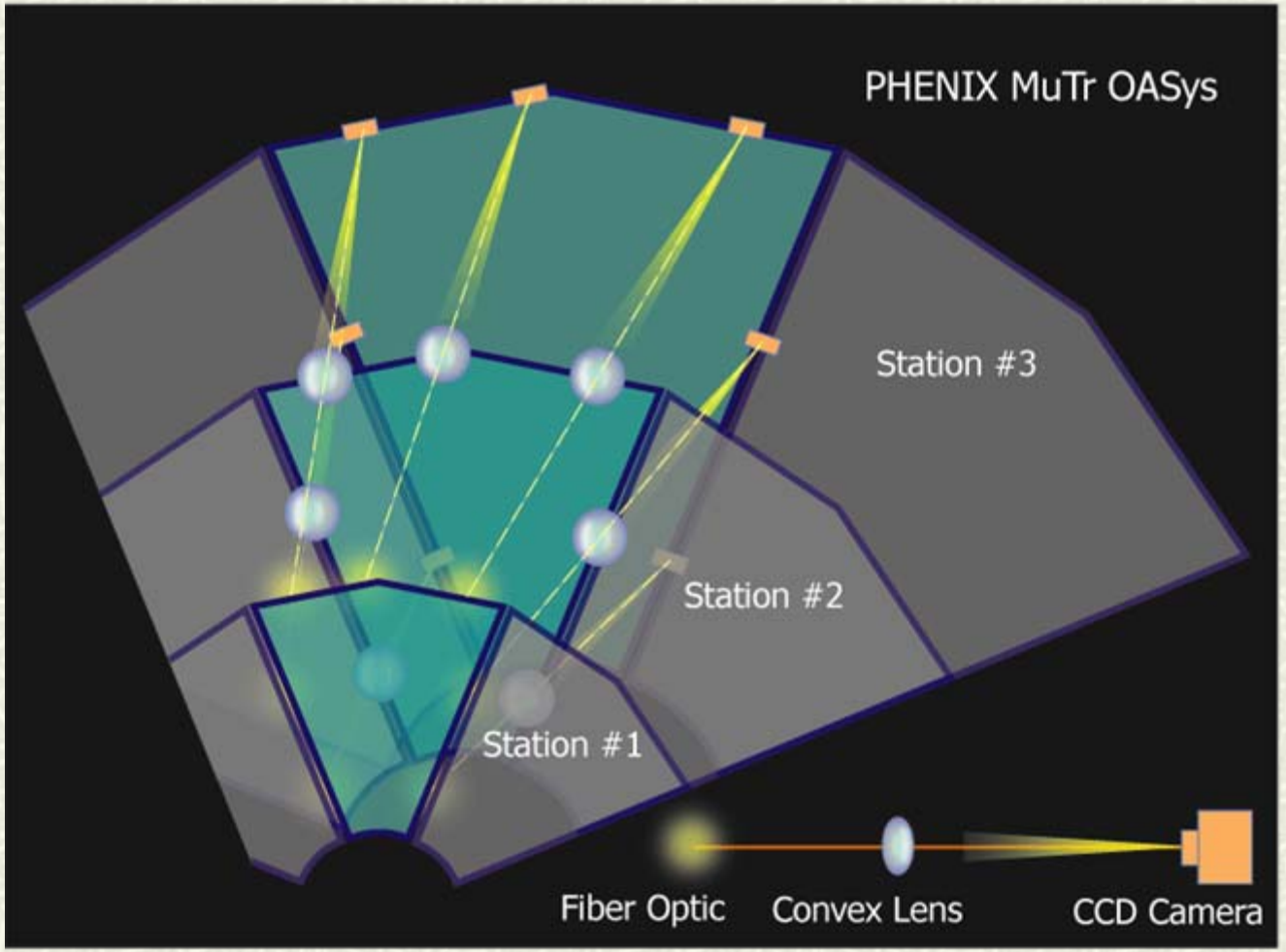


Required Chamber Position Resolution 25micron

Thermal Deformation, etc. ~ 100micron

Optical Alignment System

Relative Straightness Monitor: 7 OASys Beams / Octant Chamber

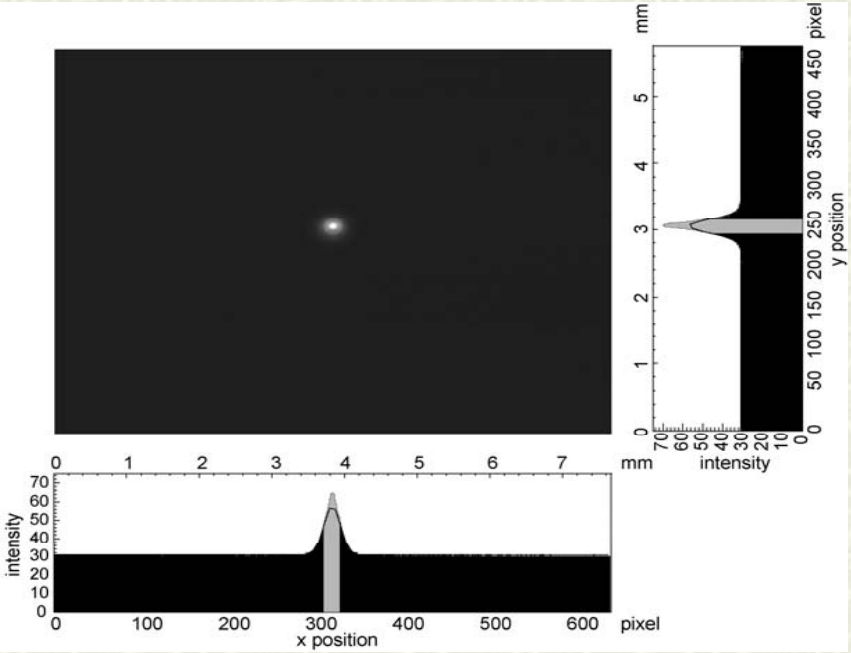


Typical Length: 1200mm:700mm

CCD Camera:
Hitachi Denshi KP-M1U
8.8x6.6mm
768Hx493V pixels
Pixel size: 11Hx13V micron

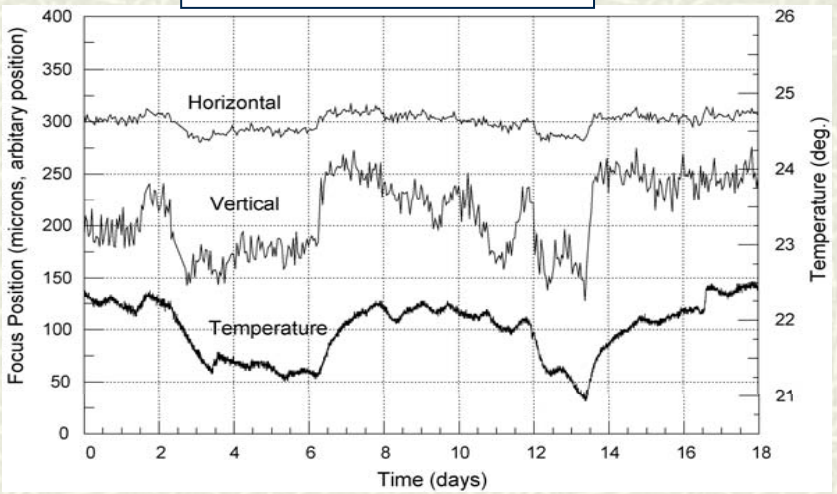
Spot Position Determination using Image Analysis

Image Analysis -> XY Center Position Determination by Gaussian Fitting



Focal Image on the CCD Camera (W/O Lens)

Time Dependence



Strong Correlation with Temperature

Ref. "Optical Alignment System for the PHENIX muon tracking chambers"
J. Murata et. al. NIMA500 (2003) 309
"Micron-Precision Optical Alignment System for Muon Tracking Chambers"
J. Murata et. al. "Muons: New Research", Nova Science
ISBN1-59454-175-2, 2004

Fluctuation and Position Resolution

Position Fluctuation
= Width of the Distribution
= Resolution of Single Flame Measurement

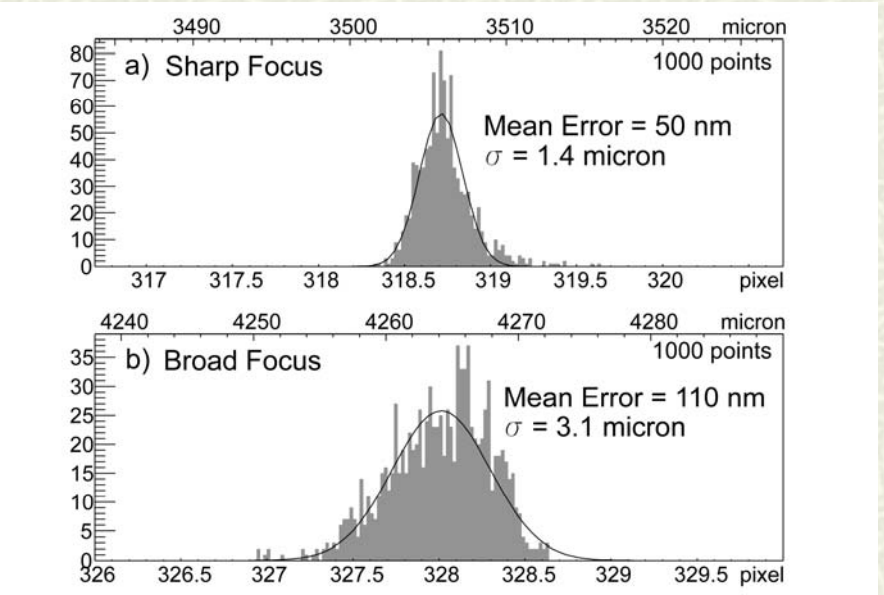
→ **~ 1 micron**

Limit: Width ~ Optical Resolution

Position Determination Error
= (Standard) Error of the Mean
= Resolution of Multi Flame Measurement

→ $\sigma(mean) \approx \frac{\sigma_{SD}}{\sqrt{n}}$ **~ 10 nm**

Limit: Mean Error < Systematic Error, Only



Large Statistics = Simply Long Exposure Time ?

Video Data :
High Statistics & Time Dep. Information

Dedicated Position Sensor

Digital Microscope ←

Olympus MIC-D
1/3inch CMOS Color Digital Camera, Zoom x250
VGA(640x480 pixel) Resolution, 10fps
Observational Field: 7.7mmx5.7mm – 0.6mm – 0.4mm

Video Capture via USB ↓

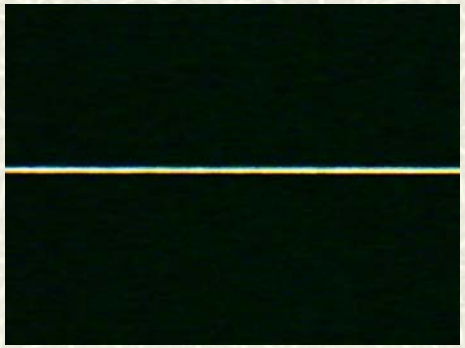
Intel Play QX3
1/3inch CMOS Color Digital Camera, Zoom x200
VGA(320x240 pixel) Resolution, 6fps
Observational Field: 7.7mmx5.7mm – 0.6mm – 0.4mm

Movie Data (AVI File) ← **10 fps, 640x480**

Adobe Premiere ↓

Image Data Sequence (BMP Files) ⇒ **Intensity Information**

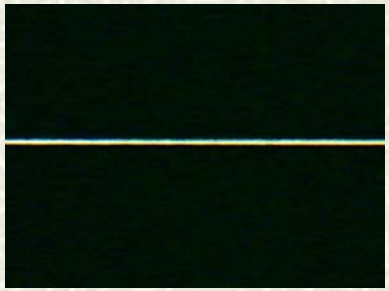
Example Object: 20micron Wire



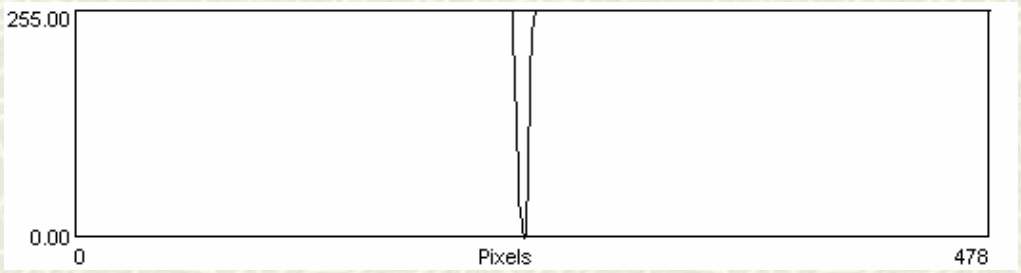
↕ **100micron**

Resolution of Toy Prototype

Scion Image Software: http://www.scioncorp.com/

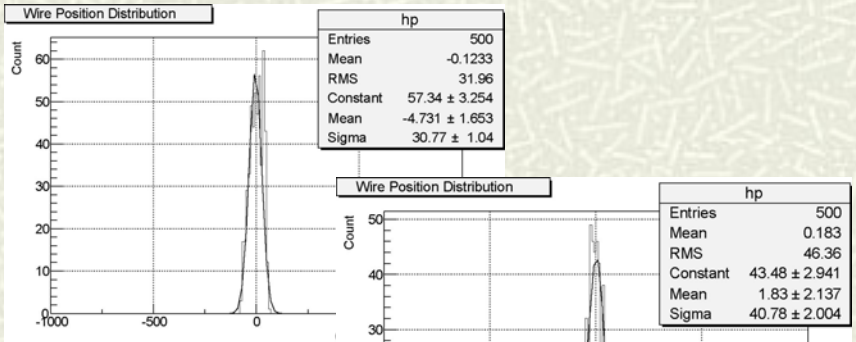


BMP File



Intensity Histograms for each flames

root analysis



Center Position Distribution: multi flame analysis

Mean Position

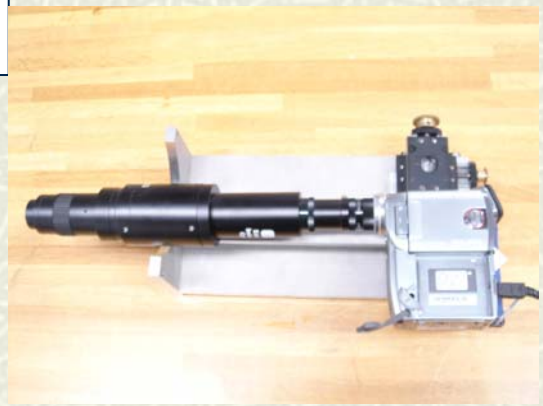
Resolution @ 500flames:
Mic-D 1.7micron
QX3 2.1micron

Digital Video Camera System

New System:
Digital Video Camera + Video Lens (Microscope)

Canon IXY DV M2
NTSC Standard
1/3.4" CCD
640x480, 29.97fps

Edmund VZM1000
FOV 0.64-2.5mm on ½" CCD
Zoom x2.5-10
Space Resolution max. 228lp/mm (4.4micron)



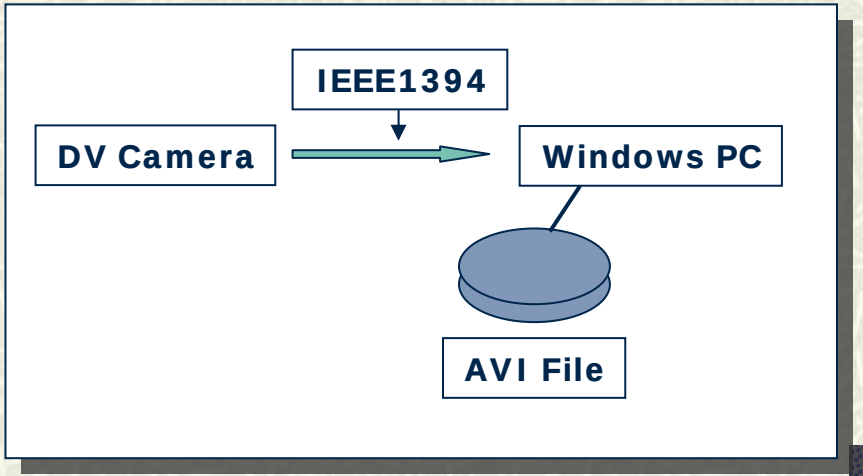
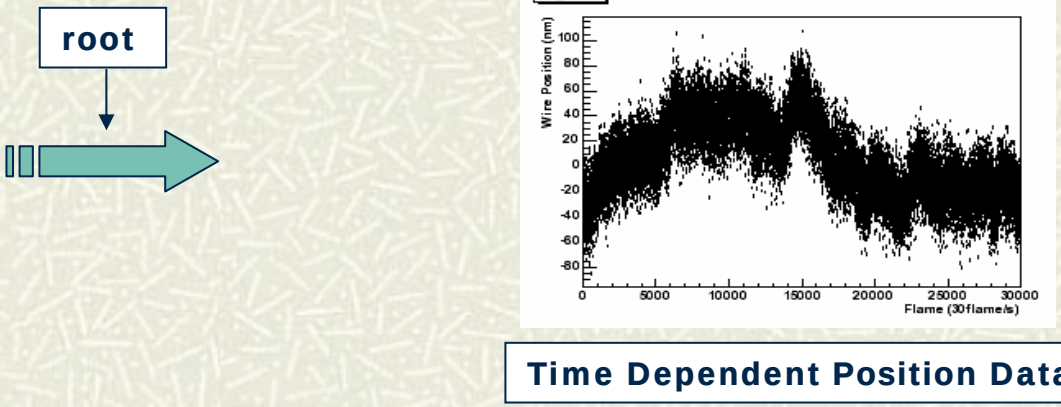
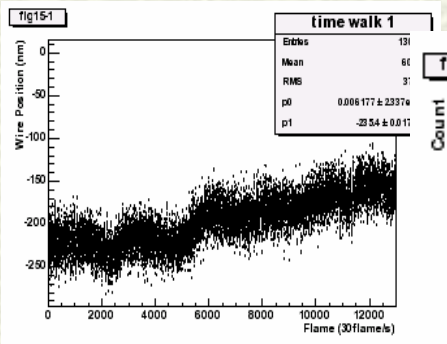


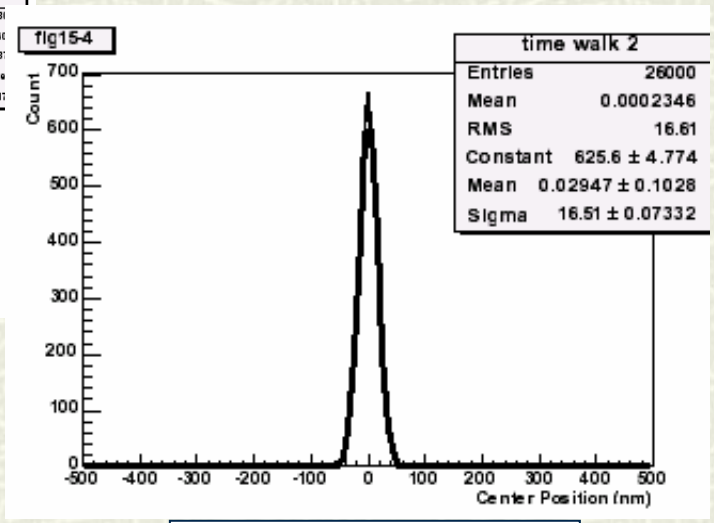
Image Processing



Resolution and Summary of Sensor R&D



Wire Position Distribution



13000flame=433sec

Rough Estimation

$$\sigma = 17nm$$

$$\sigma(mean) = \frac{\sigma_{SD}}{\sqrt{n}} \cong 100\,pm$$

Measured Resolution (Mean Error)=103pm

Dinamic Range = 500micron
Resolution = 0.00002% ~ 10^-7

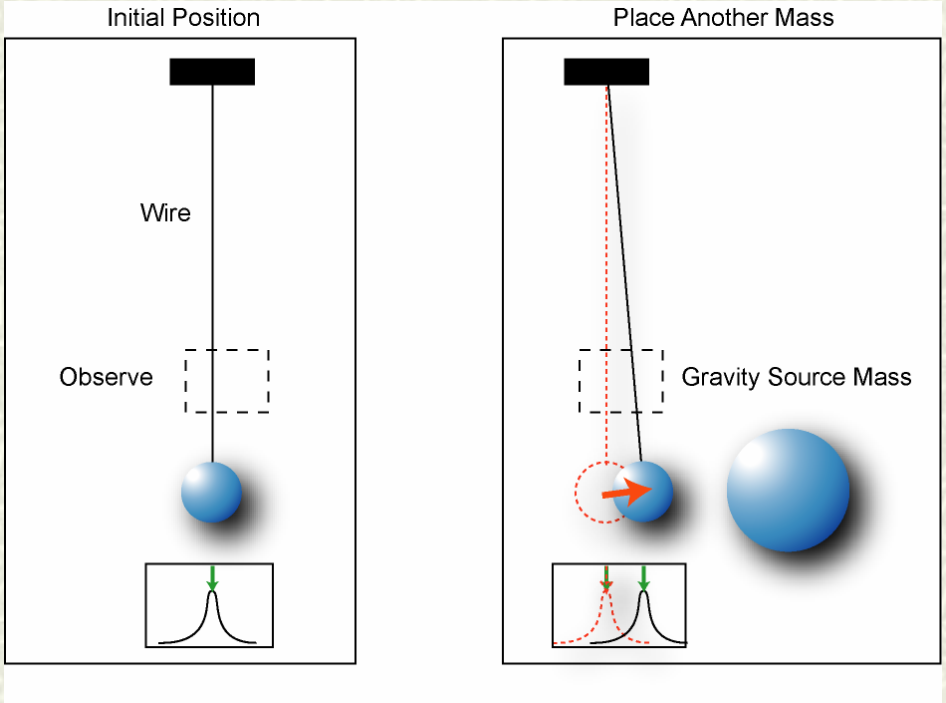
Summary

- Extremely Precise Resolution of 100pm can be obtained by very cost-effective device.
- Very wide dynamic range of 500micron gives 0.00001% resolution.
- 100pm precision corresponds to 400sec time scale measurement.
- Time scale of 1sec gives 3nm precision.
- This system is suitable for precision position measurement of moving objects.

Application: Short Range Gravity Experiment

Wide Dynamic Range, Precision Position Measurement

→ **Extremely weak force measurement, by observing displacement**



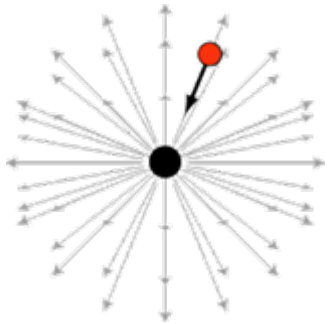
In cm scale,
Gravitational Force ~ 10nN
Displacement ~ 1nm (1m pendulum)

→ **1nm > Resolution !**

Modification of Newton's Law at Small Scale ?

Space-Time Dimensions of String Theory = 10 dimensions
Extra Dimensions = Planck Scale (10^{-33}cm) Compactified ?
Only Reason: 4D Newtonian Gravity at Long Distances

⇨ **Possible Large Extra Dimension:**
No Experimental Confirmation of the 4D Newtonian Gravity at Short Distances
Compactification Scale can be mm – micron scale



Gauss's Law in 3D ⇩

Newton's Law = Inverse Square Law

Standard Model Fields: Trapped to 3D-brane

⇨ **r^-2 dependence**

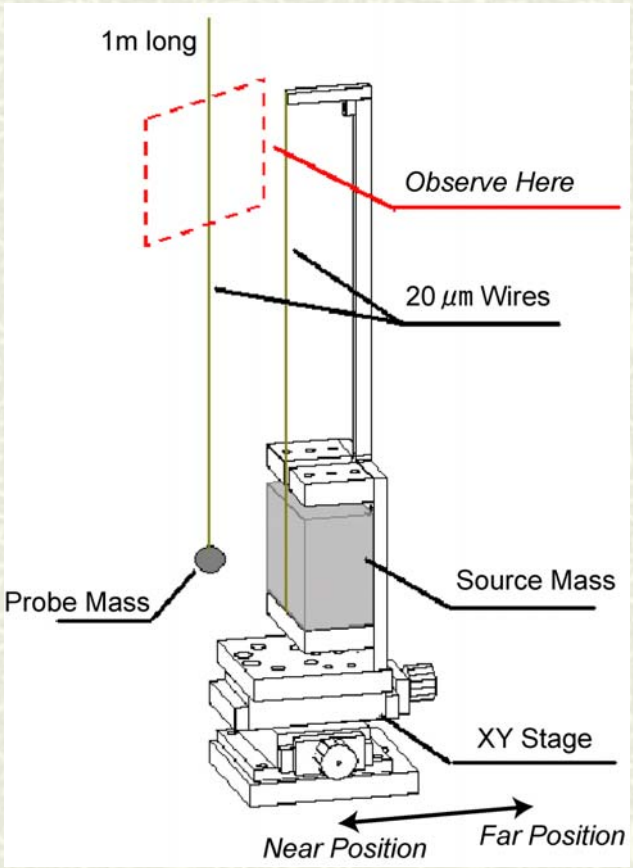
Gravitational Field: Free in Bulk Space

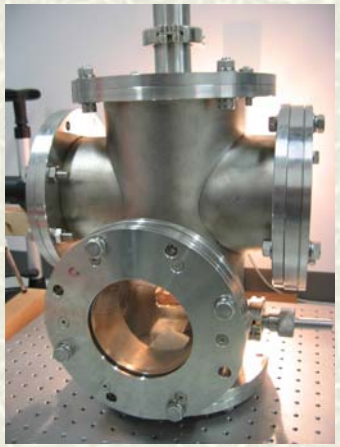
⇨ **r^-(2+d) dependence in 3+d dimension space inside compactification scale (mm-micron ?)**

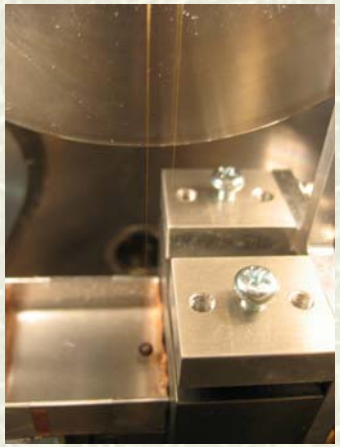
Experimental Test of Newton's Law below mm scale !

Pendulum Experiment 2003

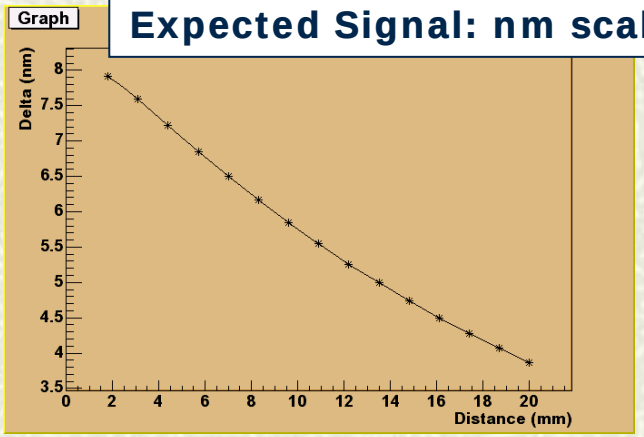
1st Step Exp. Using 1m long Pendulum



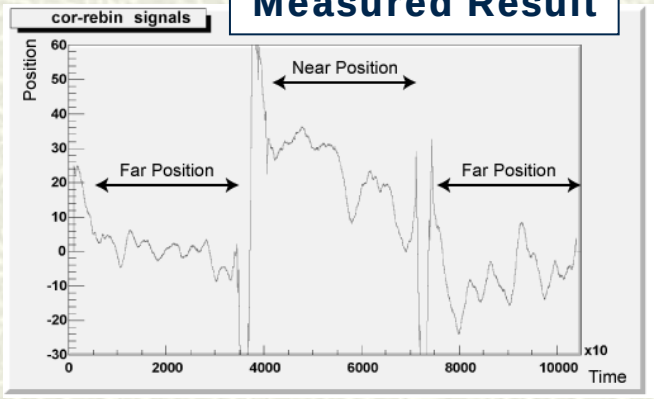




Expected Signal: nm scale



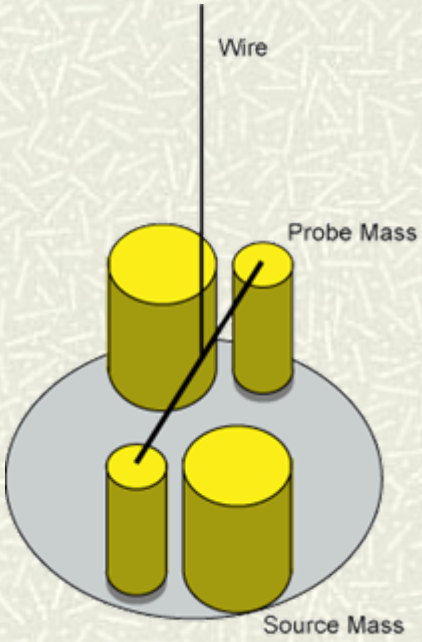
Measured Result

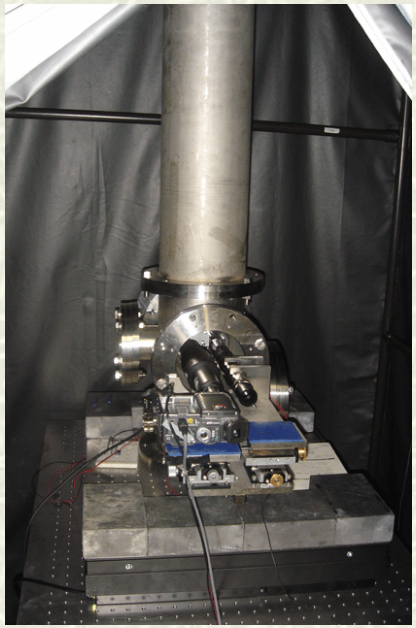


Confirmation of Gravity

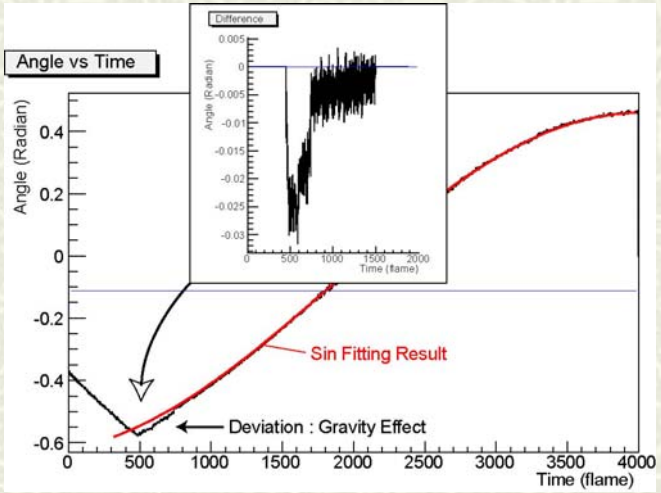
Torsion Balance Bar Experiment 2005

Exp. Using Torsion Balance Bar





Angular Motion



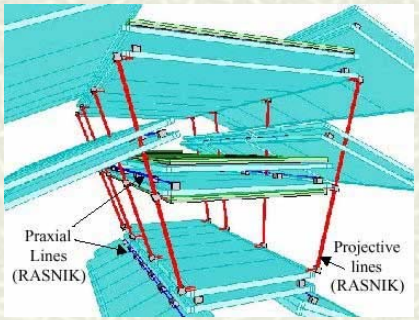
Total Acceleration = Spring Force + Gravity

Gravitational Force as Function of Distance

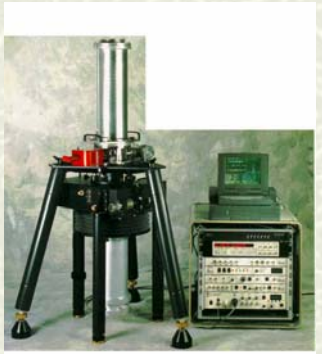
Possible Applications

Physics Experiment:

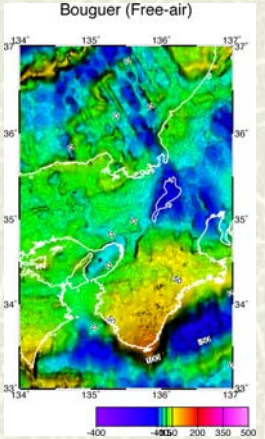
- **Particle Detector Geometry Monitor**
- **Short Range Gravity Experiments, Gravitational Wave Experiments**
- **Local Earth Gravity Measurement for Geophysics**
- **Earthquake Sensor**



ATLAS, muon alignment



U. Tokyo, G sensor

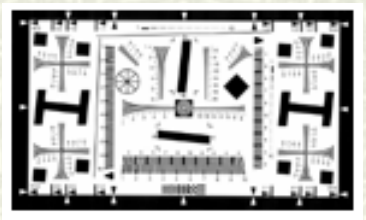


Kanazawa U
G map

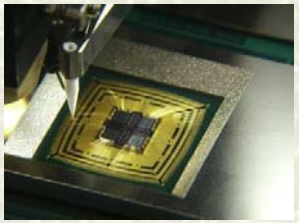
Industry:

- **Quality Assurance**
- **Hardware Gauge**
- **Wire Bonding Sensor**
- **Robot Eye**

KEYENCE
line sensor



Edmund
optics test target



Shinkawa
wire bonding

ananova
robot eye