# Monitoring Temperature and Fan Speed Using Ganglia and Winbond Chips 

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Prepared in partial fulfillment of the requirements of the Office of Science, U.S. Department of Energy Science Undergraduate Laboratory Internship (SULI) Program under the direction of Yemi Adesanya in the Scientific Computing and Computing Services group at Stanford Linear Accelerator Center.

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## Table of Contents

Abstract ..... page 3
Introduction ..... page 4
Methods and Materials ..... page 6
Results ..... page 8
Conclusion ..... page 10
Acknowledgements page 11
References ..... page 11
Figure 1 ..... page 9
Figure 2 ..... page 10

# Monitoring Temperature and Fan Speed using Ganglia and Winbond Chips <br> CAITIE MCCAFFREY (Cornell University, Ithaca NY 14850) YEMI ADESANYA (Stanford Linear Accelerator Center, Menlo Park, CA, 94025) 


#### Abstract

Effective monitoring is essential to keep a large group of machines, like the ones at Stanford Linear Accelerator Center (SLAC), up and running. SLAC currently uses Ganglia Monitoring System to observe about 2000 machines, analyzing metrics like CPU usage and I/O rate. However, metrics essential to machine hardware health, such as temperature and fan speed, are not being monitored. Many machines have a Winbond w83782d chip which monitors three temperatures, two of which come from dual CPUs, and returns the information when the sensor command is invoked. Ganglia also provides a feature, gmetric, that allows the users to monitor their own metrics and incorporate them into the monitoring system. The programming language Perl is chosen to implement a script that invokes the sensors command, extracts the temperature and fan speed information, and calls gmetric with the appropriate arguments. Two machines were used to test the script; the two CPUs on each machine run at about $65^{\circ}$ Celsius, which is well within the operating temperature range (The maximum safe temperature range is $77^{\circ}-82^{\circ}$ Celsius for the Pentium III processors being used). Installing the script on all machines with a Winbond w83782d chip allows the SLAC Scientific Computing and Computing Services group (SCCS) to better evaluate current cooling methods.


## Introduction

The Scientific Computing and Computing Services group (SCCS) provides computing and communications support for the Stanford Linear Accelerator Center (SLAC). SCCS is in charge of providing the computing power for the various projects at SLAC including BaBaR , which is studying the asymmetry of matter and anti-matter, the Gamma Ray Large Area Space Telescope project (GLAST), the Large Synoptic Survey Telescope (LSST), and the Kavli Institute for Particle Astrophysics and Cosmology (KIPAC). All of the SLAC laboratory projects require large amounts of computing power and data storage. In order to accommodate the needs of the labs SCCS has an entire floor in building 50 dedicated to housing the machines. The room was built specifically to store the machines, it includes a raised floor and is heavily air conditioned to help keep the machines from overheating. Also in order to accommodate all the groups at SLAC a number of operating systems are used including Solaris, Red Hat Linux, Windows, and Mac OS X.

In order to keep such a large number of machines up and running Ganglia, a distributed monitoring system for high performance computing systems, is used to monitor machine metrics such as the percentage of CPU being used, the amount of memory used, and I/O rate [1]. Ganglia's software periodically polls the monitored machines' metrics in order to update graphs and the round robin database (RRD). Ganglia is designed for use on systems composed of clusters and grids; at SLAC the nodes are organized into clusters by project or by the type of work a machine does. Ganglia is currently used to monitor about 2000 of SLAC's machines.

Ganglia is an excellent tool in a few ways. First it operates on multiple operating systems. It is also scalable, since it does not increase overhead for every machine but increases on the order of number of clusters [1]. Ganglia also uses a RRD, a system used to store and display time series data so that only a fixed amount of disk space is needed but a seemingly infinite amount of data can be stored. Old data is compressed by averaging it with past data, thereby freeing up disk space for new data. The averaging decreases the granularity of the graphs when viewing longer time scales, but allows the user to see machine metrics over long time periods without having to constantly increase disk space. Ganglia also creates web pages containing graphs and machine statistics from the monitored metrics. These measurements can be viewed on a cluster scale or at the machine level, allowing numerous machines to be monitored and providing information about past performance so that should a problem arise, the data can be used to find a solution.

One problem with Ganglia is that the metrics it measures are fairly generic since it is designed to be used on a broad range of hardware and software. Ganglia does not automatically monitor some critical components of hardware health, such as temperature. Monitoring temperature is extremely important because machine hardware is only guaranteed to work correctly within a specific temperature range. Should the machines operate outside this range, the machine behavior can become unpredictable.

In order to compensate for the lack of personalization Ganglia allows the user to write their own code to monitor other metrics. At SLAC, many of the machines have Im_sensor chips on the motherboard. Lm_sensors are a collection of chips that monitor power supply voltages, fan speeds, and hardware temperatures, and make this
information available to the user. In order to more efficiently monitor the machines, a Perl interface is developed to monitor temperature and fan speed by utilizing the functionality of $I m$ _sensor chips

Perl is the language chosen for the task of implementing the temperature monitoring. Perl falls in the gap between low level programming languages (like C) which are fast with unlimited uses, and high level shell programming which is slower, but requires shorter code. [4]. Perl will always be slower than a language like C or C++ because it is interpreted by Perl's interpreter and not compiled into byte code and stored in an executable file. Perl is designed for programs that work with text $90 \%$ of the time and do other things $10 \%$ of the time. In particular, Perl's extensive regular expressions, and portability across platforms makes it an ideal choice.

## Materials \& Methods

Ganglia has a hierarchical architecture. Individual machines are at the lowest level running gmond, the Ganglia Monitoring daemon. Gmond runs in the background polling machine metrics (CPU usage, I/O rate, etc.) at various intervals and sending this metrics to receiving channels specified by a configuration file. [3]. Ganglia was developed at Berkley and is open source.

Gmetric, the Ganglia metric tool, allows users to expand the base of metrics monitored by gmond. Users can write scripts to monitor metrics on individual machines then invoke the gmetric command passing a configuration file, a metric name, the metric value, the type of value (string, unsigned integer, signed integer, etc), and the units of the
metric. Gmetric sends the data to all the receiving channels specified in the configuration file the data travels up the hierarchy to periodically update the RRD [3].

The original script was designed to run on a group of 510 batch machines referred to as "nomas". The nomas all have a Tyan Thunder LE-T V1.07 motherboard containing two Pentium III processors. The Tyan motherboards all contain an Im_sensorcompatible chip, the Winbond w83782d, which monitors power supply voltages, up to three fan speeds, and up to three temperatures [2]. The information monitored by the Winbond chip can be accessed by running the "sensors" command.

A Perl script entitled "temp-fanWatch" was written to monitor temperature and fan speeds. The script works by invoking the "sensors" command and storing the remaining text lines in an array. Each line is checked to see if it contains fan speed information or thermal data. If it does the appropriate gmetric call is made. The program then sleeps for a number of minutes and repeats the process.

The program also tracks temperature rate of change from query to query by saving the previous temperature data. The previous temperature data is used to determine the change per sample rate. If any of the temperatures measured are changing at a rate greater than the specified trigger rate (default $1^{\circ}$ Celcius) then the sample time will decrease. If the sample time is not decreased and the rate of change on any of the temperatures equals the trigger rate the sample time remains the same. If all of the change rates are less than the trigger rate, the sample time is increased.

The sample time is decreased by a power of the variable "decrement" which is user specified (defaults to 0.9). The power is calculated based on the thermal input with
the greatest change rate per sample time. The new number of minutes is calculated using the following formula:

New Sample Time $=$ decrement $\wedge$ (change/trigger) $*$ current sample time.

This way the sample time decreases more rapidly when the change rate per sample is larger.

The sample time is increased by the inverse of the "decrement". The new number of minutes is calculated using the following formula:

New Sample Time = current sample time / decrement

It does not increase more quickly if the rate of change is smaller. This is to prevent the sample time from growing large quickly just because the rate of change was small or non existent for one sample. If the sample time grew on the same scale that the sample time decreased the script would be more likely to miss data in the event that a sudden change occurred.

## Results

The script is performing well. It was tested on two machines noma0449 and noma0450. Figure 1 and Figure 2 show some of the graphs produced by the RRD as a result of running "temp-fanWatch" on the machine noma0449. The script will be installed on all of the nomas machines to achieve a better picture of operating
temperature, but the two CPUs on each of the monitored nomas operate at 64-65 degrees Celsius on a regular basis.



Figure 1. Graphs showing the monitored temperatures of the two Pentium processors on the machine noma0449. The graphs were taken on Monday August $14^{\text {th }} 2004$ and show the data collected over the previous week.


Figure 2. Graphs showing the speeds of the two fans on noma0449's motherboard. The graphs were taken on Monday August 14, 2006 and show the accumulated data over the past week.

## Conclusion

The two monitored noma machines used in creating the Perl script are running at acceptable temperatures since the maximum operating temperature range for the Pentium III processors is $77^{\circ}-82^{\circ}$ degrees Celsius. This suggests that present cooling methods are effective; however, the script will need to be installed on the entire noma cluster to fully evaluate present cooling efforts.

Also, although the script was written specifically for the nomas it can be placed on any machine with a similar Winbond chip. The portability of this script will allow
many more machines to be monitored, giving a better understanding of SLAC's machine hardware health.

## Acknowledgements

The authors would like to thank the U.S. Department of Energy Office of Science for the SULI internship opportunity. Special thanks to Yemi Adesanya for all his help and guidance throughout the project.

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# Development of Powder Diffraction Analysis Tools for a Nanocrystalline Specimen: 

## An Emphasis upon NiTi (Nitinol)

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August $25^{\text {th }}, 2006$

Prepared in partial fulfillment of the requirements of the Office of Science, U.S. Department of Energy Science Undergraduate Laboratory Internship (SULI) Program under the direction of Dr. Apurva Mehta of the Stanford Synchrotron Radiation Laboratory (SSRL) at the Stanford Linear Accelerator Center (SLAC).

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## Table of Contents

Abstract ..... iii
Introduction ..... 1
Materials and Methods ..... 2
Results and Discussion ..... 3
Conclusions ..... 6
Acknowledgements ..... 7
References ..... 7
Figures ..... 8


#### Abstract

Development of Powder Diffraction Analysis Tools for a Nanocrystalline Specimen: An Emphasis upon NiTi (Nitinol). ERICH OWENS (Albion College, Albion, MI 49224) MATTHEW STRASBERG (Cornell University, Ithaca, NY 14850) APURVA MEHTA (Stanford Linear Accelerator Center, Menlo Park, CA 94029), SAMUEL WEBB (Stanford Linear Accelerator Center, Menlo Park, CA 94029)

Powder diffraction is a specialized technique whose investigatory limits are constrained by the scale of the crystallized substance being scanned versus the probe beam used. When disparate in scale, with the photon spot size larger than the crystal being probed, many are employed, the resulting diffraction image being cast from all possible incident angles, constructing $\chi$-arcs containing information about the crystalline structure of the material under examination. Of particular interest to our collaboration is the structure of Nitinol, a superelastic Nickel-Titanium alloy, whose phase transformations and load bearing deformations can be studied by usage of diffraction, with wide sweeping biomedical uses. Analysis of this data is complicated by phase transformation and material fluorescence, which make difficult the computational modeling of the peaks within concentric $\chi$-arcs. We endeavored to construct a series of computational tools (the amalgamation of them known as 2DPeakFinder) for refining and extracting this relevant data, toward the end of employing previously developed algorithms in the material's structural analysis. We succeeded to a large degree with the use of an iterative algorithm to navigate radial complexity of the signal and manage to retain a distinction between useful signal and superfluous background noise. The tools developed in this project are a small step in readily streamlining the analysis and physical modeling of a Nanocrystalline material's structural properties.


## INTRODUCTION

Visual inspection is the most direct way to examine an item's structure. When it comes to molecular arrangements, however, the visible light spectrum fails us as its associated wavelengths are too large to probe the microscopic structures we're concerned with. Higher energy photons (namely, x-rays), having thus smaller wavelengths, must therefore be employed. A complication emerges when the size of the probe beam is larger than the grain-size of the sample, exposing many different crystal orientations resulting in diffraction arcs or rings. Techniques and tools for interpretation of this "smeared" diffraction patterns - often called powder pattern-- are thus necessary. This necessity is acute when investigating nano-crystalline materials, as it is not yet possible to make sufficiently intense x-ray probes of nanometer dimensions. There a wealth of information contained in these powder diffraction patterns. For example, Bibee in 2005 [3], showed that it is possible to extract the full strain tensor from the distortion of diffraction rings in a 2D powder diffraction pattern-our collaboration refined these mathematical relationships [2]. It also appears possible to extract crystallite orientation information, commonly referred to as sample texture, from a 2D powder diffraction pattern. This relevant information is accessible within the bright arc fringes of a diffraction image (see figure 1), particularly the location of these fringes' peak intensity, location of said peak from a determined center, as well as the relative width of these fringes. We refer to the azimuthal angle as $\chi$, and the radial angle $2 \theta$ as consequence of Bragg's law:

$$
\lambda=2 \mathrm{~d} \operatorname{Sin}[\theta]
$$

Q subsequently is defined as the geometric relation between $2 \theta$ detailed below and can be interpreted visually as the radial distance.

$$
\mathrm{Q}=4 \pi \operatorname{Sin}(\theta) / \lambda
$$

A material when subjected to load will strain. The macroscopic deformation of the material can arise from many different mechanisms at a microscopic level and can be easily distinguished by a diffraction experiment. The microdeformation can be due to elastic deformation of the atomic bonds. This type of deformation results in distortion of the powder rings, as shown by [1]. The microdeformation can be also due to creation of dislocations, or slip on 'slip planes'. This form
of deformation results in broadening of powder rings. In some very heavily twinned (highly texturized with a clear bipolar distribution of intensities by value of $\chi$ ) material the microdeformation can be due to transformation of one set of twins into another mechanical more favorable form. This type of microdeformation changes the texture of the sample and hence redistributes the location of bright fringe intensity in a diffraction ring.

We propose to develop various software tools and techniques for powder diffraction analysis that will easily and quickly extract diffraction peak position, width, and intensity information as a function of the azimuthal $\chi$ angle. We will apply these tools to understand deformation of Nitinol, which exhibits all three modes of micostrains [2].

## MATERIALS AND METHODS

## Diffraction and Data Collection

The powder diffraction data utilized was collected by Apurva Mehta and collaborators from Nitinol Devices \& Components (hereafter NDC). Thin strips in a dogbone conformation were measured with constant incident angle with the routine powder method [1]. The strips were pulled in a tensile strain-inducing rig until critical fracture. The diffractometer was newly calibrated at each load increment.

## Processing of Signal

The 2D raw data files as collected by the diffractometer are more easily worked in diffraction related coordinate space instead of a Cartesian pixel space. The collected the images resemble a series of continuous, concentric rings and arcs. Program Fit2D [4] was used to transform these images into the diffraction coordinates of Q and and $\chi$ (figure 2).

The newly processed data sets present a series of rows representing $\chi$, with a characteristic central peak of high relative intensity to the surrounding intensity values (figure 6 ). The primary problem presented is then distinguishing background from signal. These lesser range of intensities may be referred to as background, and for our purposes detract from the desired data describing the central peak, which we'll call signal. This may be specified by a user, however as
viewed in figure 2, there is not a common range for signal along all values of $\chi$. Exhaustive specification of this range by the use is possible, but time intensive, so efforts are to be made in automating this process. Background intensity is a common artifact in diffraction patterns, resultant often from material fluorescence, scattering from the air in the collimator and beam stop, or diffuse scattering resulting from crystal imperfections [1]. The problem then posed is detecting this background intensity level, determining its characteristic distribution (constant, linear, or more complex relationship) then subtracting in some fashion from the data. At this point some mathematical function may be modeled to fit the remaining central peak, with goodness of fit and residue between it and that modeled used to gauge the success of such a process. The use in having such a model is that the peak's intensity, location and width may then easily be calculated for exportation.

## RESULTS AND DISCUSSION

## Overview

A successful scheme was developed to address an iterative approach toward processing the caked (integrated along axes of $\chi$ and Q , which are polar coordinates in the pixel space the image was taken in) diffraction patterns. The program developed will hereafter be referred to as "2DPeakFinder". The first $\chi$ row is displayed to the user as a cross section in pixel space. He or she is prompted to input the range to search for the desired peak. A mean is calculated of the background, and is subtracted from the signal and the data outside the user's specified range is nullified. A Gaussian fit is made with three determined coefficients, in the form of:

$$
\left.a_{1} e^{-\left(\left(x-b_{1}\right) / c_{1}\right.}\right) .
$$

This sufficing as our employed mathematical fitting model. The fit's peak location (corresponding to $\mathrm{b}_{1}$ ), peak intensity $\left(\mathrm{a}_{1}\right)$, and peak width $\left(\mathrm{c}_{1}\right)$ is recorded for later file output. The determined range for the row is used for the next, but the location of the next row's halfmaxima (allowing for calculation of the Gaussian distribution's width) as they deviate from the previous row readjusts the program's peak search range. This is repeated onwards. The results may be appreciated qualitatively in figures 2 through 5, the second set projected upon a false z-
axis representing intensity. The data recorded to a separate file is converted to values of Q and scaled against $\chi$, as referenced by an external file set by the provider of caked data with reference to what the range of appropriate values are. That data included are column vectors of the fitted rows' Gaussian peak intensities, peak widths, and peak location, ran against a steadily increasing index reflective of which Q value these correspond to.

## Background and Signal

With the underlying assumption that the program precedes upon, that some data is essentially background and the rest relevant signal (contained within one peak). Within the algorithm, the assumption results in a strict demarcation of this with two variables storing the endpoints of this range. Complications therefore arise with the presence of supernumerary diffraction lines (manifested as peaks in the row space the data is processed), often resulting from cell distortion and phase transformations [1]. Figure 6 is a cross-section of caked austenite diffraction data, around $\mathrm{Q}=29$, along $\mathrm{Chi}=-59$ (this was chosen as representative of most of the data this program intends to process, at least with regard to austenite samples, with the most possible complexity the authors have seen). The supernumerary peaks are clearly visible. Figure 7 outlines the cross section seen in $5(\mathrm{Chi}=-179$ around $\mathrm{Q}=29$ for a relative macrostrain of 500 micrometers) with a few added dimensions. The background calculation was based on a mean calculation, yielding a constant value to be subtracted. The resulting data was then nullified (set to zero) at all points except the range indicated to be signal. Due to the negation of the outside regions of the signal, if relevant signal is within the cutoff region as is used for a naïve fit then it would not contribute to the determination. The inherent assumption in this approach does not accommodate for complex background patterns that may vary by value of Q [1]. Similarly, the data sets encountered in development of 2DPeakFinder were revealed to be polluted by Martensitic imperfections, whose presence create supernumerary peaks adjacent to the central desired one (see figure 6), whose presence we both do not desire in calculation of a constant mean (not representative of a constant additional signal to our relevant peak) but whose presence casts inaccuracies in the curve fitting (figure 10). The authors suggest a more complex scheme, whose approach fundamentally differs in selecting not a binary state of good or bad data sections, but rather a series of points indicating representative background data points, then
relying upon a cubic interpolating spline distribution fit upon these to subtract out a suitably complex model.

## Peak Shape

A Gaussian fit was employed for the current version of 2DPeakFinder, however an examination of the residue of this fit (between the background negated signal as determined by the iterative algorithm and the three coefficient fit as employed by the 'fit' function of the Matlab Curve Fitting Toolbox [5], see Figure 10) reveal it is not entirely representative of the peak we intend to fit. The clear deficiency appears toward the base of the distribution, implying greater accuracy with usage of a Lorentzian/Cauchy distribution, whose characters shape is that with a wider and longer trailing tail than the Gaussian/Doppler profile. Preferably some convolution of the two, known as a Voigt distribution should be employed. Examination of the residue in detail allows for determination of goodness of fit, among other things, and thus is computed by 2DPeakFinder (Figures 8 and 9). The primary goal of our collaboration's study of Nitinol is extraction of the strain tensor, which is primarily fueled by the location of peaks, secondarily from the distribution of intensities (which is used as a weighting factor in the determination of the tensor) . Thus the discrepancies between the original data's maximum value in the peak search range and the Gaussian fit's peak location, as well as the relative intensities of the fits to the original data convey important information about the goodness of our model. We calculated the deviation between the maximum points of the original data set of Austenite data centered around $\mathrm{Q}=42$ at 440 relative micrometers of strain, and that of the fit's peak locations, and encountered surprising results. There was presented a mean deviation of 1.6685 pixels (see figures 13 and 14). This is statistically significant and indicative of a standard asymmetry to the peaks in the data set that was not previously understood. A more robust fitting system would accommodate the data and fit for this. Further investigations too are required as to whether this is the true nature of the prominent signal peak or contribution from sample-specific Martensitic phase pollution.

## Transitioning from $1 D$ to $2 D$ : Iterative Approach

The $\chi$ rings we've been examining are not perfect circles. When radially transformed into the caked images we're familiar with (Figure 2) this results in a contour indicative of the elliptical
nature of the $\chi$-valued intensities. As a result, a specified range for signal against background cannot be fixed, but rather adaptive. From a practical standpoint, is not time effective for a user to define these ranges for every value of $\chi$ for each Q-focused caked image for each set of strained and location specific data. Rather, 2DPeakFinder takes a user inputted declaration of the range of relevant signal for the first row in pixel space of the data. It follows the steps described earlier in the paper, and fits this. It uses the same range for the next row down using the same specifications for the signal range. However, after this point the disparity between its peak location and the peak location of the row before it is calculated, this value used to adjust the range values left or right as needed. The underlying assumption then is of direct continuity in the $\chi$-ring and expectation of small shifts by Q of relevant signal per row in pixel space. The former case is encountered when we use 2DPeakFinder to process caked data focused upon $\mathrm{Q}=51$ at high stress levels, as a result of shadowing from the grips used to apply the relative strain, about $500 \mu \mathrm{~m}$ or above (Figures 11 and 12). The missing data poses a problem for the iterative algorithm, which operates off the assumption of direct continuity. Table 1 details the progression of the fits made and the problems encountered within the data. Around $\chi=-35$ the data begins to be shadowed. This results in missing background signal; subsequently the calculated mean is an underestimate of the data we'd expect. As a result, the fitted peak in a row with missing background will possess overestimated peak intensity. As the shadow in the data engulfs the actual relevant signal (as can be interpolated), the iterative algorithm begins to fit a false peak that then corresponds solely of the remaining background juxtaposed with the nullified remainder of the data (see $\chi=0$ in Table 1). When the shadowing diminishes and the signal properly reappears, due to the slight adjustments within the range of the iterative algorithm in fitting data and reevaluating the proper range for signal, there is significant lag displayed in returning to proper values (see $\chi=25$ in Table 1).

## CONCLUSIONS

The fits constructed by the developed program 2DPeakFinder appear accurate within the most general considerations. Their application to the analysis of diffraction data is specific and robust for that which has continuity within all values of $\chi$, and where usable signal is interpreted to be a symmetric distribution which is evenly separated from undesirable constant background by a simple specification of a single range. Within this paper we presented for your consideration
cases where these assumptions failed, and a detailed analysis of those events. The iterative approach was largely successful, and minimized user input. Future approaches would consider largely more complex background regression models, routines to compensate for shadowed or missing data-- which our algorithm managed to traverse only for virtue of there existing some remaining background for it to fit. Despite this, there was significant lag in its response to modeling existent data once it encountered true data again, and that is to be minimized. Also of particular import would be determination of the most appropriate mathematical model used in fitting the central peaks within our data. The studies of calculated residue and deviations indicated both a general inadequacy of the Gaussian distribution, due to the broader base of the actual signal and its apparent asymmetry.

## ACKNOWLEDGEMENTS

I'd like to thank Apurva Mehta for his role as my mentor this summer, I learned more about the continuing process of science and its communication than I thought possible. I'd also like to thank my collaborator and friend Matthew Strasberg for his role in these projects this summer, as well as the contributions of Samuel Webb, Monica Barney, and David Bronfenbrenner. Thank you as well to Stephanie Majewski for her valuable assistance Also of importance are the facilities of the Stanford Synchrotron Radiation Laboratory, the Stanford Linear Accelerator Center, and the Office of Science through the Department of Energy for making all of this possible.

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FIGURES AND TABLES


Figure 1 - Diffraction Image of Nitinol in Martensite Phase under load. Note the characteristic bright fringes arranged in mostly continuous \& concentric arcs.


Figure 2 - Caked Ring, Top-down false color image


Figure 3 - Caked ring, processed with the developed iterative algorithm, Top-down false color image.


Figure 4-(45 deg, 35 deg ) view of false color/false axised unprocessed data

## 



Figure 5 - ( $45 \mathrm{deg}, 35 \mathrm{deg}$ ) view of a false color/false axised processed data


Figure 6 - NiTi in Austenite phase diffraction sample cross section. The sample is under a relative strain of 500 micrometers. The image is data focused along $Q=29$ along $\mathbf{C h i}=-59$. Note the multiple peaks in addition to the prominent central peak.


Cross-section of Chi $=-59$ of austenite NiTi
diffraction sample under a relative strain of 500 micrometers. Various stages of data processing displayed.
——Original data with background subtracted and mullified
——Data fitted to a gaussian
——Original Data

- Calculated constant background level

Figure 7 - Similar to Figure 5, but now showing the various stages of file processing. Original data minus displayed constant calculated background, as well as the subsequent fit.


Figure 8 - Residue, top-down false colored view

## 



Figure 9 - Residue from processed data of 500 micrometers of relative strain around $Q=\mathbf{2 9}(\mathbf{3 5 , 4 5})$ degree view


Figure 10 - Cross-section displaying negated background, a Gaussian fit, and the residue.


Figure 11 - Example of shadowing in high strain ( 500 micrometers) data around $\mathbf{Q}=51$.


Figure 12 - Fit of shadowing case, note the fits to erratic background within the discontinuity


Figure 13 - Histogram displaying deviation in peak locations between the data set and the fit of arbitrarily chosen Austenite Chi ring around $Q=42$ at 440 micrometers of relative strain


Figure 14 - Comparisons of the peak locations between raw data and fit sets. Note the general shift and asymmetry of the difference. Units are in pixel space.

Table 1 - Selected cross sections of data centered around $\mathbf{Q}=51$ for high strain cases and the iterative algorithms partially successful attempts to traverse the shadowed data.

| Data Location | Image | Comments <br> Fits peaks from -179 onwards <br> with no difficulty. |
| :---: | :---: | :---: |
| $\chi=-121$ |  | The shadowing progresses <br> downwards from Q, the effect <br> upon background can be <br> observed. Signal is <br> diminished. |
| $\chi=-19$ | $\chi=0$ |  |

# The Effect of the Earth's Atmosphere on LSST Photometry 

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August 25, 2006

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## TABLE OF CONTENTS

Abstract ..... ii
Introduction ..... 1
Materials and Methods ..... 3
Results ..... 6
Discussion and Conclusions ..... 7
Acknowledgments ..... 9
References ..... 9


#### Abstract

The Effect of the Earth's Atmosphere on LSST Photometry. ALEXANDRA S. RAHLIN (Massachusetts Institute of Technology, Cambridge, MA 02139) DAVID L. BURKE (Kavli Institute for Particle Astrophysics and Cosmology, Stanford Linear Accelerator Center, Stanford, CA 94025).

The Large Synoptic Survey Telescope (LSST), a ground-based telescope currently under development, will allow a thorough study of dark energy by measuring, more completely and accurately than previously, the rate of expansion of the universe and the large-scale structure of the matter in it. The telescope utilizes a broadband photometric system of six wavelength bands to measure the redshifts of distant objects. The earth's atmosphere makes it difficult to acquire accurate data, since some of the light passing through the atmosphere is scattered or absorbed due to Rayleigh scattering, molecular absorption, and aerosol scattering. Changes in the atmospheric extinction distribution due to each of these three processes were simulated by altering the parameters of a sample atmospheric distribution. Spectral energy distributions of standard stars were used to simulate data acquired by the telescope. The effects of changes in the atmospheric parameters on the photon flux measurements through each wavelength band were observed in order to determine which atmospheric conditions must be monitored most closely to achieve the desired $1 \%$ uncertainty on flux values. It was found that changes in the Rayleigh scattering parameter produced the most significant variations in the data; therefore, the molecular volume density (pressure) must be measured with at most $8 \%$ uncertainty. The molecular absorption parameters produced less significant variations and could be measured with at most $62 \%$ uncertainty. The aerosol scattering parameters produced almost negligible variations in the data and could be measured with $>100 \%$ uncertainty. These atmospheric effects were found to be almost independent of the redshift of the light source. The results of this study will aid the design of the atmospheric monitoring systems for the LSST.


## INTRODUCTION

The Large Synoptic Survey Telescope (LSST) is a ground-based telescope that is currently under development to be stationed in Cerro Pachón, Chile. It is designed with a $3.5^{\circ}$ field of view and will take 3-gigapixel charge-coupled device (CCD) images of about 20,000 square degrees of the visible sky every three nights. The short time scale between consecutive images allows for time-lapse images of rapidly developing celestial objects such as supernovae. Additionally, the large amount of data to be collected by the telescope in very short periods of time will open the door for studying dark energy much more accurately than in the past.

The LSST will use a broadband photometric system, shown in Figure 1, to collect spectra over six wavelength bands between 350 and 1050 nm . The photometric efficiencies as a function of wavelength for each of the LSST's six filter bands (U, G, R, I, Z and Y), calculated in [1], include each of the filter response functions as well as the quantum efficiency of the CCD camera (Figure 2).

The LSST will be used to make accurate measurements of redshifts in light coming from various distant celestial objects. The redshift $z$ with a measured wavelength $\lambda$ and an expected wavelength $\lambda_{0}$ is defined as the fractional difference between the two wavelengths:

$$
\begin{equation*}
z=\frac{\lambda-\lambda_{0}}{\lambda_{0}} \tag{1}
\end{equation*}
$$

The redshift of an object can be measured by observing characteristic shapes in its spectral energy distribution (SED), such as in the Balmer absorption lines of hydrogen that are visible in the $400-500 \mathrm{~nm}$ range. For an object moving away from the earth when light is emitted from it, the wavelength of each of its Balmer lines will appear closer to the red end of the spectrum than it would be if the object were at rest.

Another method of measuring redshifts is to take advantage of the LSST's broadband photometric system, which measures the total photon flux through each wavelength band. Certain redshift values correspond to characteristic flux ratios between the bands. Either
type of redshift measurement depends on correctly analyzed SEDs, so the uncertainty in flux measurements must be minimized in order to obtain accurate results.

Measuring the redshifts of many objects accurately is critical for characterizing the nature of dark energy. The invariant line element $d s^{2}$ for a flat universe is defined as:

$$
\begin{equation*}
d s^{2}=-c^{2} d t^{2}+a^{2}(t) d \vec{x}^{2} \tag{2}
\end{equation*}
$$

Edwin Hubble's observations of galactic redshifts [2] demonstrate that the universe is expanding, so the scale factor $a(t)$ is larger today than it was in the past. The rate of change of the scale factor is defined by the Hubble parameter:

$$
\begin{equation*}
H(t)=\left(\frac{\dot{a}}{a}\right)^{2} \tag{3}
\end{equation*}
$$

This parameter determines whether the expansion is accelerating or decelerating. The scale factor can be measured over time, relative to the scale factor today $(t=0)$, as a function of the redshift $z$ of an object whose light began its travel to Earth at an earlier time $t$ :

$$
\begin{equation*}
1+z=\frac{a(0)}{a(t)} \tag{4}
\end{equation*}
$$

Measuring the redshifts of many distant galaxies provides a large data sample for characterizing the time evolution of (3). Earlier results [3, 4] show that the expansion of the universe is accelerating; the cause of this acceleration is unknown and is attributed to "dark energy" - a form of energy that is not yet understood.

The Earth's atmosphere presents an obstacle in acquiring accurate redshift data, because the LSST is a ground-based telescope. As light enters the atmosphere from various objects in the sky, the spectrum acquired changes by various conditions such as fluctuations in air pressure, temperature, and particle content. This process is called atmospheric extinction. The transmittance of the light coming through the atmosphere at various wavelengths has a char-
acteristic shape, shown in Figure 3. The shape of the distribution at shorter wavelengths is dominated by elastic Rayleigh scattering by air molecules much smaller than the wavelength of incident light. The intensity of Rayleigh scattering varies as $\lambda^{-4}$, so shorter wavelengths scatter more significantly. At longer wavelengths, the dominant effects are optical scattering by aerosols (dust, water droplets, silicon, etc.) with an approximate $\lambda^{-1}$ dependence, and molecular absorption of vapors $\left(\mathrm{H}_{2} \mathrm{O}, \mathrm{O}_{2}, \mathrm{O}_{3}\right.$, etc. $)$ at wavelengths of $700-1000 \mathrm{~nm}$.

Because the atmosphere above the telescope is changing constantly, it is difficult to isolate the spectral energy distribution (SED) of a distant star or galaxy due to changes created by the atmosphere. The goal of this project was to determine the stability of various known SEDs with respect to changes in atmospheric conditions. It was expected that most atmospheric fluctuations would affect the signal by only a few percent; however, it was found that the data were more sensitive to changes in the Rayleigh scattering parameter than to changes in the molecular absorption and aerosol scattering parameters. This has study determined which atmospheric conditions would need be monitored most closely in order to ensure that redshift data could be accurately corrected.

## MATERIALS AND METHODS

## Generation of Atmospheric Extinction Data

Atmospheric extinction distributions over wavelengths of 300 to 1200 nm were generated by making changes to the atmospheric distribution in Figure 3, which can be characterized by an exponential function with four free parameters:

$$
\begin{equation*}
A\left(\lambda ; \alpha_{R}, \alpha_{M}, \alpha_{A}, \alpha_{P}\right)=\exp \left(-\left[k_{R}\left(\lambda ; \alpha_{R}\right)+k_{M}\left(\lambda ; \alpha_{M}\right)+k_{A}\left(\lambda ; \alpha_{A}, \alpha_{P}\right)\right]\right) . \tag{5}
\end{equation*}
$$

Each $k$ is called an extinction coefficient. The Rayleigh scattering extinction coefficient:

$$
\begin{equation*}
k_{R}\left(\lambda ; \alpha_{R}\right)=\alpha_{R}\left(\frac{\lambda}{300}\right)^{-4.05} \tag{6}
\end{equation*}
$$

is driven mostly by the atmospheric pressure. The wavelength in (6) is normalized so that $\alpha_{R}$ is a dimensionless constant.

The molecular absorption extinction coefficient:

$$
\begin{equation*}
k_{M}\left(\lambda ; \alpha_{M}\right)=\alpha_{M} f(\lambda) \tag{7}
\end{equation*}
$$

contains information about the shapes of the lines due to absorption by $\mathrm{H}_{2} \mathrm{O}, \mathrm{O}_{2}$, ozone and other airborne molecules. The water content of the atmosphere changes with humidity, so the molecular absorption parameter is affected by both temperature and pressure; however, for the purposes of this study, the functional form of $f(\lambda)$ was defined by the shape of the absorption lines in the sample distribution.

The aerosol scattering extinction coefficient:

$$
\begin{equation*}
k_{A}\left(\lambda ; \alpha_{A}, \alpha_{P}\right)=\alpha_{A}\left(\frac{\lambda}{300}\right)^{-\alpha_{P}}, \quad \text { where } \quad 0.5<\alpha_{P}<1.5 \tag{8}
\end{equation*}
$$

is affected by atmospheric temperature and pressure, as well as winds that spread aerosols throughout the atmosphere. The wavelength in (8) is again normalized so that $\alpha_{A}$ is dimensionless. The spectral index $\alpha_{P}$ varies with the size of the aerosols. The cross section for scattering by larger aerosols is less dependent on the wavelength of incident light, therefore, the spectral index is closer to zero.

The Rayleigh and aerosol scattering parameters $\alpha_{R, 0}$ and $\alpha_{A, 0}$ for the atmospheric distribution in Figure 3 (solid black line) were obtained from a nonlinear least-squares fit (dashed red line) to the function $\exp \left[-\left[k_{R}\left(\lambda ; \alpha_{R, 0}\right)+k_{A}\left(\lambda ; \alpha_{A, 0}, 1\right)\right]\right]$. The result of the fit determined the initial values of $\alpha_{R, 0}=1.089$, and $\alpha_{A, 0}=0.071$ with a $\chi^{2}$ per degree of freedom of 5.74.

The large $\chi^{2}$ value is due mostly to the fact that the fit does not explicitly include the ozone absorption dip (near 600nm in Figure 3). Parameters $\alpha_{M, 0}$ and $\alpha_{P, 0}$ were both initialized to 1 . New atmospheric distributions were generated by varying each initial $\alpha$ parameter by factors of up to $\pm 100 \%$. For example, changing $\alpha_{R}$ to $\alpha_{R}=0.1 \alpha_{R, 0}$ decreased the Rayleigh scattering extinction coefficient by a factor of ten, thus generating a new atmospheric extinction distribution, $A\left(\lambda ; 0.1 \alpha_{R, 0}, \alpha_{M, 0}, \alpha_{A, 0}, \alpha_{P, 0}\right)$.

Various regions of the ( $\alpha_{R}, \alpha_{M}, \alpha_{A}$ ) parameter space were explored by fixing two of these three factors at their initial values and varying the third by up to $\pm 100 \%$. The ranges of atmospheric extinction distributions generated by this method are shown in Figure 4. The effects of each of these distributions were quantified as discussed in the following section. The ( $\alpha_{A}, \alpha_{P}$ ) parameter space was explored as well.

## Measurement of Atmospheric Extinction

Several sets of standard data were used to analyze the atmospheric effects on LSST photometry. Spectral energy distributions (SEDs) for various stars were collected from [5]. The SED of a giant star from the catalog is shown in Figure 5.

The SED data $S(\lambda)$ were integrated with the response $T(\lambda ; f)$ of each filter band $f$ to simulate the true photon flux $\Phi_{\text {true }}(f, S)$ through each filter band:

$$
\begin{equation*}
\Phi_{t r u e}(f, S)=\int S(\lambda) T(\lambda ; f) d \lambda \tag{9}
\end{equation*}
$$

The measured photon flux $\Phi_{\text {meas }}(\lambda ; f, S, A)$ of each star was simulated by integrating its SED with an atmospheric extinction distribution $A\left(\lambda ; \alpha_{R}, \alpha_{M}, \alpha_{A}, \alpha_{P}\right)$ and the response of a particular LSST filter $T_{L S S T}(\lambda ; f)$ that included the CCD quantum efficiency:

$$
\begin{equation*}
\Phi_{\text {meas }}(f, S, A)=\int S(\lambda) A\left(\lambda ; \alpha_{R}, \alpha_{M}, \alpha_{A}, \alpha_{P}\right) T_{L S S T}(\lambda ; f) d \lambda \tag{10}
\end{equation*}
$$

The filter response functions are shown in Figure 2, and Figure 5 displays the true and
measured flux per wavelength through each filter band for a sample giant star.
A correction factor $C$ for approximating the true flux from measured values was calculated for each filter band from the subset of Dwarf stars in the star catalog:

$$
\begin{equation*}
C(f, A)=\frac{1}{N} \sum_{\text {Dwarfs }} \frac{\Phi_{\text {true }}(f, S)}{\Phi_{\text {meas }}(f, S, A)} \tag{11}
\end{equation*}
$$

Corrected flux values, $\Phi_{\text {corr }}(f, S, A)=C(f, A) \Phi_{\text {meas }}(f, S, A)$, were obtained for each of the giant and supergiant stars in [5] and plotted against their true values. Trends in the $\Phi_{\text {corr }}$ distributions were measured as functions of variations $(\Delta \alpha)$ in each $\alpha$ parameter; i.e. a distribution generated using $\alpha_{R}=\alpha_{R, 0}$ corresponded to $\Delta \alpha_{R}=0 \%$. Figure 6 shows the $\Phi_{\text {corr }}$ distribution in the G band with a third-order polynomial fit, along with the ideal line $\left(\Phi_{\text {corr }}=\Phi_{\text {true }}\right)$. Corrections to the measured flux were expected to fall within $1-2 \%$ of the true flux for each SED and filter. For each filter band, trends in the data generated from the variations on the reference atmosphere were observed by means of changes in the mean bias of the fit from the ideal line, and the width of the distribution about the ideal line.

## RESULTS

Figure 7 shows the residuals of each corrected flux distribution from the ideal line in the G band for various values of $\Delta \alpha_{R}$, with the remaining three atmospheric parameters fixed to their initial values. $\Delta \alpha_{R}$ was varied at uniform intervals between $\pm 20 \%$, while the remaining three parameters were varied between $-80 \%$ and $+100 \%$.

The trends in the bias of each distribution from the ideal line and the width about the ideal line are shown in Figure 8 for the G band as functions of $\Delta \alpha_{R}, \Delta \alpha_{M}$ and $\Delta \alpha_{A}$. Figure 8 also shows the bias and width as functions of $\Delta \alpha_{A}$ for three values of $\Delta \alpha_{P}$. Similar data for the bias and width were collected for each of the five remaining wavelength bands.

An analysis of the trends due to the effects of various atmospheric parameters in measured data determined the requisite accuracy to which each parameter would have to be measured
to ensure at most $0.1 \% \Phi_{\text {true }}$ contribution to the uncertainty from each $\alpha$ parameter in the fit bias $\left(\sigma_{\text {bias }, \alpha}\right)$ and at most $1 \% \Phi_{\text {true }}$ uncertainty in the distribution width ( $\sigma_{\text {width }, \alpha}$ ). Assuming that the data in Figure 8 follow a linear trend, the slope of each line provides the relationship between the uncertainty in each $\alpha$ parameter and the uncertainty in the bias and width. Table 1 shows the percentage accuracy required in each $\alpha$ parameter for each wavelength band to ensure that $\sigma_{\text {bias }, \alpha}<0.1$ and $\sigma_{\text {width }, \alpha}<1$. Such accuracy in characterizing atmospheric fluctuations reduces the total uncertainty on the corrected flux data.

## DISCUSSION AND CONCLUSIONS

Variations in the Rayleigh scattering parameter, $\alpha_{R}$, produce the largest variations in corrected flux measurements, especially in the lowest wavelength bands, U and G. Figure 8 demonstrates that a $20 \%$ increase in $\alpha_{R}$ changes the fit bias by almost 0.3 and the width by almost 0.5 . The results in Table 1 show that the Rayleigh scattering parameter must be measured to within at most $8 \%$ in the lowest wavelength band. It is known that the Rayleigh scattering extinction coefficient, which depends on the volume density of small particles (radius $\ll$ incident wavelength), varies mostly with pressure. This volume density can be accurately measured, because $\alpha_{R}$ does not vary by more than $1-2 \%$ throughout the year[6].

Variations in the molecular absorption parameter, $\alpha_{M}$, produce significant variations in the data only in the regions with absorption lines that appear in the three highest wavelength bands ( $\mathrm{I}, \mathrm{Z}$ and Y ) for the atmospheric model used in this study. According to Table $1, \alpha_{M}$ must be measured to within at most $62 \%$ uncertainty. However, this model takes into account only changes in the water content of the atmosphere and assumes that the volume density of other molecules, such as ozone and various oxides, remains constant over time and space. Ozone, sulfur dioxide, ammonia and other variable density molecules constitute about one
tenth the volume of water molecules in the atmosphere [7], thus the effects of these molecules are not as significant as those of water. A more thorough atmospheric model would take into account variations in density of these molecules as well.

The aerosol scattering parameters $\alpha_{A}$ and $\alpha_{P}$ affect the atmospheric extinction distribution almost uniformly across all wavelength bands (Figure 4), but the effects are not significant enough to cause sensitivity to these parameters in the data. According to Table 1 , the uncertainty on both parameters can be $>100 \%$ in all wavelength bands.

The method of analyzing atmospheric effects discussed in this paper was applied to the spectral energy distribution of galaxy Sbc from [8]. Figure 9 shows the difference in residuals between two pairs of adjoining wavelength bands as functions of redshift, using the initial atmospheric parameters for the atmospheric distribution. These differences in wavelength bands are called "colors" and are used to analyze the chemical makeup of galaxies. The colors fluctuate with redshift by up to several percent $\Phi_{\text {true }}$. These fluctuations are significant and must be accounted for in analyzing distant galaxies.

Changes in atmospheric parameters produce a linear trend in the colors. Figure 10 shows two colors as functions of $\Delta \alpha_{R}$ at zero redshift. The slope of the color vs. $\Delta \alpha_{R}$ data is plotted as a function of redshift in Figure 11. Because the slope does not fluctuate by more than $1 \%, \alpha_{R}$ can be determined with similar accuracy for galaxies at each redshift.

The effects of atmospheric extinction vary with space and time due to changes in temperature, pressure and wind patterns that carry particles throughout the area surrounding the telescope, so as the LSST moves across the sky, it must account for these atmospheric changes in real time. The results of this study provide a good understanding of how the various sources of atmospheric extinction compound the uncertainty on flux data collected by the LSST, and may aid the design of the atmospheric monitoring systems for the telescope. The proposed model [7] is an auxiliary telescope for measuring variation in standard stars due to atmospheric extinction. These standard stars will be used to calibrate measurements taken by the LSST using the method implemented in this study. Ideally, calibrated flux
measurements collected by the LSST should be within $1 \%$ of the true flux, thus requiring the fit bias and the width about the true flux to be less than $1 \% \Phi_{\text {true }}$. Bias and width values of $>1 \% \Phi_{\text {true }}$, such as those in Figure 8, are due to the intrinsic spread in the data, so reducing these values to less than $1 \% \Phi_{\text {true }}$ requires a deeper understanding of the structure of the spectral energy distributions.

## ACKNOWLEDGMENTS

First and foremost, I would like to thank my mentor, David Burke, for his guidance. I would also like to thank the program directors and Mike Woods for giving me the opportunity to work at SLAC on a project that was entirely new to me. Finally, I would like to thank the Office of Science and the Department of Energy for funding this internship.

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## TABLES

Table 1: Maximum percent uncertainty allowed for each $\alpha$ parameter in (5) so that the uncertainty due to each $\alpha$ on the bias is $\sigma_{\text {bias }, \alpha}<0.1 \% \Phi_{\text {true }}$ and the uncertainty on the width is $\sigma_{\text {width }, \alpha}<1 \% \Phi_{\text {true }}$. Such accuracy in the measurement of atmospheric parameters ensures minimal contribution to the uncertainty on the data due to atmospheric fluctuations.

|  | Maximum allowed uncertainty |  |  |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\sigma_{\text {bias }, \alpha}<0.1 \% \Phi_{\text {true }}:$ |  |  |  |  |  |  |  |  | $\sigma_{\text {width }, \alpha}<1 \% \Phi_{\text {true }}:$ |  |  |  |
| Filter | $\% \alpha_{R}$ | $\% \alpha_{M}$ | $\% \alpha_{A}$ | $\% \alpha_{P}$ | $\% \alpha_{R}$ | $\% \alpha_{M}$ | $\% \alpha_{A}$ | $\% \alpha_{P}$ |  |  |  |  |  |
| U | 9.19 | $\gg 100$ | 295 | 394 | 39.6 | $\gg 100$ | $\gg 100$ | $\gg 100$ |  |  |  |  |  |
| G | 7.77 | $\gg 100$ | 122 | 230 | 50.4 | $\gg 100$ | 793 | $\gg 100$ |  |  |  |  |  |
| R | 67.1 | $\gg 100$ | 498 | $\gg 100$ | 343 | $\gg 100$ | $\gg 100$ | $\gg 100$ |  |  |  |  |  |
| I | 420 | 537 | $\gg 100$ | $\gg 100$ | $\gg 100$ | $\gg 100$ | $\gg 100$ | $\gg 100$ |  |  |  |  |  |
| Z | $\gg 100$ | 81.5 | $\gg 100$ | $\gg 100$ | $>100$ | 333 | $\gg 100$ | $\gg 100$ |  |  |  |  |  |
| Y | $\gg 100$ | 62.3 | $\gg 100$ | $\gg 100$ | $\gg 100$ | 366 | $\gg 100$ | $\gg 100$ |  |  |  |  |  |

## FIGURES



Figure 1: Optical layout of the LSST. The filters are placed 6 cm from lens 3 (L3), as shown, and select for light in six different wavelength bands. Wavefronts entering the telescope are distorted by the optics and atmosphere through which the light travels. Thus, telescope images are distorted into point spread functions (lower right) with a typical FWHM of $0.6^{\prime \prime}$ due to atmospheric distortion. These images demonstrate that the uncertainty due to atmospheric effects must be reduced in order to reduce uncertainty in the data, since optical effects are much less significant (Credit: LSST Corporation).


Figure 2: Response functions for each of the six proposed filter bands for the LSST (dashed lines), and response functions that take into account the quantum efficiency of the CCD camera (solid lines).


Figure 3: Typical extinction distribution of light entering the atmosphere as a function of wavelength, from [1]. The absorption lines for oxygen and water are illustrated. The range of wavelengths where each extinction process is most significant is also shown. This particular distribution was approximated using (5) with values $\alpha_{R, 0}=1.089, \alpha_{M, 0}=1, \alpha_{A, 0}=0.071$ and $\alpha_{P}=1$.


Figure 4: Atmospheric distributions for high and low values of each $\alpha$ parameter.


Figure 5: The spectral energy distribution of a giant star (\#90 in [5]). The dashed colored lines show the flux distributions in each filter band. The solid colored distributions include the quantum efficiency of the CCD camera, as well as the atmospheric effects. The integrals of the dashed and solid distributions across each filter band correspond to (9) and (10), respectively. The measured flux is calculated using the atmospheric extinction distribution in Figure 3.


Figure 6: The distribution of corrected flux values in the G band for each of the giant and supergiant stars in [5], fit to a third-order polynomial. The bias of the fit from the ideal line $\left(\Phi_{\text {corr }}=\Phi_{\text {true }}\right)$ and the width of the distribution about the ideal line were calculated for various changes in the atmospheric parameters.


- $\Delta \alpha_{R}=-20 \%$
- $\Delta \alpha_{R}=-15 \%$
- $\Delta \alpha_{R}=-10 \%$
- $\Delta \alpha_{R}=-5 \%$
- $\Delta \alpha_{R}=0 \%$
- $\Delta \alpha_{R}=5 \%$
- $\Delta \alpha_{R}=10 \%$
- $\Delta \alpha_{R}=15 \%$
- $\Delta \alpha_{R}=20 \%$ - - - Ideal

Figure 7: Distribution of residuals ( $\Phi_{\text {corr }}-\Phi_{\text {true }}$ ) across the G band for various values of the Rayleigh scattering parameter $\alpha_{R}$, while $\alpha_{M}, \alpha_{A}$ and $\alpha_{P}$ remain fixed to their initial values. The bias of each fit from the ideal line $\left(\Phi_{\text {corr }}=\Phi_{\text {true }}\right)$ and the width of each distribution about the ideal line were calculated for each of the distributions shown above.

(a) Fit bias and width about the ideal line as functions of $\Delta \alpha_{R}, \Delta \alpha_{M}$ and $\Delta \alpha_{A}$ in the G band.

(b) Fit bias and width about the ideal line as functions of $\Delta \alpha_{A}$ for three values of $\Delta \alpha_{P}$ in the G band.

Figure 8: Small variations in the bias and width imply a lower constraint on the corresponding $\alpha$ parameter, such that the uncertainty in the bias and width is within $0.1 \%$ of the true flux. Larger variations in the bias and width imply a tighter constraint on the $\alpha$ parameter. The variations in trends for each value of $\Delta \alpha_{P}$ in (b) show that the flux values vary as the aerosol content of the atmosphere changes in particle size and density.


Figure 9: Residuals of colors $\mathrm{G}-\mathrm{R}$ (a) and $\mathrm{R}-\mathrm{I}$ (b) as functions of redshift for galaxy Sbc in [8].


Figure 10: Residuals of colors $\mathrm{G}-\mathrm{R}$ (a) and $\mathrm{R}-\mathrm{I}$ (b) as functions of $\Delta \alpha_{R}$ for galaxy Sbc in [8].


Figure 11: Slope of data in Figure 10 as a function of redshift.

# Thermal Analysis of the ILC Superconducting Magnets 

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August 24, 2006

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## TABLE OF CONTENTS

Abstract ..... ii
Introduction ..... 1
Materials and Methods ..... 2
Results ..... 6
Discussion and Conclusions ..... 7
Acknowledgments ..... 9
Appendix 1: The ASME Pressure Vessel Codes ..... 10
References ..... 11
Figures and Tables ..... 12


#### Abstract

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Critical to a particle accelerator's functioning, superconducting magnets serve to focus and aim the particle beam. The Stanford Linear Accelerator Center (SLAC) has received a prototype superconducting quadrupole designed and built by the Centro de Investigaciones Energticas, Medioambientales y Tecnolgicas (CIEMAT) to be evaluated for the International Linear Collider (ILC) project. To ensure proper functioning of the magnet, the device must be maintained at cryogenic temperatures by use of a cooling system containing liquid nitrogen and liquid helium. The cool down period of a low temperature cryostat is critical to the success of an experiment, especially a prototype setup such as this one. The magnet and the dewar each contain unique heat leaks and material properties. These differences can lead to tremendous thermal stresses. The system was analyzed mathematically, leading to ideal liquid helium and liquid nitrogen flow rates during the magnet's cool-down to 4.2 K , along with a reasonable estimate of how long this cool-down will take. With a flow rate of ten gaseous liters of liquid nitrogen per minute, the nitrogen shield will take approximately five hours to cool down to 77 K . With a gaseous helium flow rate of sixty liters per minute, the magnet will take at least nineteen hours to cool down to a temperature of 4.2 K .


## INTRODUCTION

Particle accelerators, which hold the key to unlocking many of the universe's deepest mysteries, require a high energy, tightly focused beam in order to probe the sub-microscopic world. The International Linear Collider (ILC) is the next step in a long series of experiments attempting to gain a peek of insight into the universe's inner workings. This next-generation particle accelerator is still in its planning stages and is projected to be completed in the late 2010s. The 30 km long accelerator will smash electrons and positrons together at a collision energy of 500 GeV [1]. As with all accelerators, success of the planned experiments relies on the ability to precisely steer and focus the beams of particles as they are accelerated down the beamline. Magnets known as dipoles are used to steer the beam, while quadrupoles are used to focus the beam. As particles reach higher energies, the magnetic fields must increase in strength in order to keep the beam properly aligned. At the beam's highest energies, the quadrupoles in the ILC must produce a magnetic field of almost 6 T , requiring a current of 100 A [2]. In traditional electromagnets, a current this large would wreak havoc through Ohmic heating, the power dissipated when a current flows through a resistive wire. As a result, the magnets designed for use in the ILC will be cooled down to their superconductive temperatures. Superconducting materials are interesting in a number of ways. They offer no electrical resistance, giving them the ability to carry enormous currents without any loss. Additionally, superconductors have the unique property of being perfectly isolated from external magnetic fields [3]. There are, however limits to these properties. In addition to a critical temperature, there are also both a critical current density and field strength above which materials lose their superconductivity [4].

The cooling process is critical not only to the magnet but to the entire particle accelerator. The superconducting quadrupole built by the Centro de Investigaciones Energticas, Medioambientales y Tecnolgicas (CIEMAT) for the International Linear Collider (ILC)
project has been brought to the Stanford Linear Accelerator Center (SLAC) in order to undergo a number of tests. The primary test will probe the produced field's magnetic center, to a precision of one micron. This center will be compared for a range of input currents, as the device was designed to be sufficiently versatile to be successfully used at all points in the beam line. As the input currents and the induced magnetic field increase, the magnet itself may significantly shift and deform due to internal magnetic stresses. A magnetic center that shifts substantially for different currents would imply that the magnet would not be suitable for use in every stage of the accelerator.

The focus of this study is to determine how best to cool the magnet to its cryogenic state. Thermal stresses must be kept to a minimum, in order to ensure safety of the magnet. The primary goal of the study is to determine reasonable estimates for cooling time, warming time, and the amounts of liquid nitrogen and helium to be used during the cooling process.

## MATERIALS AND METHODS

## General Setup

The quadrupole itself is composed of three concentric cylinders, with a bore through their centers. This axial hole is the tunnel through which the particles travel. The thin, innermost cylinder contains the turns of tiny superconducting ribbons of wire mixed with copper, embedded into an epoxy. Outside of this cylinder lies the iron yoke, whose function is to shape and strengthen the magnetic field produced by the current. The outermost shell is an aluminum compression ring; it maintains its shape, even as the iron and copper deform during the cooling.

The magnet is housed inside of a vessel, which is initially filled with liquid helium (LHe) through the bottom. After the vessel is filled, the bottom line is shut off, and the helium level is maintained by filling as necessary from the top. The rate of this filling process, and
the corresponding cooling, are to be calculated. The area outside of this vessel is a vacuum, in order to reduce unwanted heat loss through convection. In order to gain administrative permission to use these vessels, it had to be shown that they comply with the American Society of Mechanical Engineers (ASME) pressure vessel codes [5] (see Appendix 1). Between the helium and vacuum vessels is a copper housing cooled by liquid nitrogen $\left(\mathrm{LN}_{2}\right)$. This shielding is designed to cut down on unwanted heating of the helium vessel via radiation.

## Cooling of the Nitrogen Shield

The nitrogen shield, composed of copper, is conductively cooled by passing $\mathrm{LN}_{2}$ through tubes wound around it. A method of energy balance was used to estimate the absolute least time necessary to cool the copper down to 77 K , the temperature at which $\mathrm{LN}_{2}$ boils. By equating the copper's heat loss with the $\mathrm{LN}_{2}$ 's gain (in vaporization plus heating, ideally, back to room temperature) and assuming $\mathrm{LN}_{2}$ flow rates, the time was computed using the following equation:

$$
\begin{equation*}
m_{\text {copper }} \Delta u_{\text {copper }}=\dot{m}_{N_{2}}\left[L_{N_{2}}+h_{N_{2}}(300 K)-h_{N_{2}}(77 K)\right] \Delta t \tag{1}
\end{equation*}
$$

Where $m_{\text {copper }}$ is the mass of copper, $\Delta u_{\text {copper }}$ is the change in internal energy of the copper, $\dot{m}_{N_{2}}$ is the mass flow rate of the liquid nitrogen, $L_{N_{2}}$ is the heat of vaporization for the liquid nitrogen, $h$ are the enthalpies of the copper, and $\Delta t$ is the change in time. The internal heat of the copper was calculated according to the Debye model:

$$
\begin{equation*}
u(T)=\frac{9 R \Theta_{D}}{8}\left[1+\frac{8 T^{4}}{\Theta_{D}^{4}} \int_{0}^{T / \Theta_{D}} \frac{x^{3} d x}{e^{x}-1}\right] \tag{2}
\end{equation*}
$$

where $R$ is the material's gas constant, $\Theta_{D}$ is the material's Debye characteristic temperature, and $T$ is the material's temperature. This model inherently considers the copper's changing thermal properties as its temperature drops [6]. Calculations of a similar type were repeated,
with different $\mathrm{N}_{2}$ exiting temperatures, slight heat leaks, and different flow rates. Heat leaks, or the amount of heat picked up by the vessel due to inherent imperfections, were included as a rate of heat loss times the amount of time taken for the cooling. Previous estimates not conducted in this study indicated a maximum heat leak rate of 20 W .

## Warming of the Nitrogen Shield

Also of interest to us is the rate at which the nitrogen shield warms up after the $\mathrm{LN}_{2}$ stops flowing. Should repairs or alterations be necessary to the shield, little work could be done at the low temperatures at which it functions. By calculating the amount of heat radiated into the vessel, we should be able to acquire a general feeling about how the shield is warming. Convection and conduction effects were not included in this calculation. The vessel is wrapped in 30 layers of multilayer insulation. As a result, the total radiation is passed through 31 transfers: from the shield to the first layer of insulation, through 29 insulation gaps, and from the last insulation layer to the walls of the vacuum vessels. The radiation transfer equation is calculated as:

$$
\begin{equation*}
T_{2}^{4}-T_{1}^{4}=\frac{\dot{Q}}{A} \frac{1}{\sigma} \sum \frac{1}{F_{n}} \tag{3}
\end{equation*}
$$

where $T_{2}$ is the external temperature, $T_{1}$ is the internal temperature, $\frac{\dot{Q}}{A}$ is the rate of heat radiated between the surfaces per unit of area, $\sigma$ is Boltzmann's constant, and $F_{n}$ is the overall emissivity factor between two interfaces [6].

## Cooling of the Magnet

The cooling process of the magnet is estimated in much the same way as that of the nitrogen shield. Again, a basic calorimetry calculation was done:

$$
\begin{equation*}
m_{\text {magnet }} c_{\text {magnet }} \Delta T_{\text {magnet }}=\dot{m}_{H e}\left[L_{H e}+h_{H e}(300 K)-h_{H e}(4.4 K)\right] \Delta t \tag{4}
\end{equation*}
$$

where $c_{\text {magnet }}$ is the magnet's specific heat and the other variables are defined in Eqn. 1 above. In order to calculate the cooling of the magnet, two factors must be taken into account. First, as mentioned above, the magnet is composed of three different materials: copper, iron, and aluminum. The thermal properties of each are very different. To compensate for these differences, the Law of Mixtures was invoked. The approximation of the entire magnet's specific heat is simply the sum of each component's specific heat times its volumetric fraction.

$$
\begin{equation*}
c_{\text {magnet }}=c_{C u} \frac{V_{C u}}{V_{\text {total }}}+c_{F e} \frac{V_{F e}}{V_{\text {total }}}+c_{A l} \frac{V_{A l}}{V_{\text {total }}} \tag{5}
\end{equation*}
$$

where $c$ represents each material's specific heat, $V$ is each material's volume, and $V_{\text {total }}$ is the total volume of the magnet.

The second factor to consider is the material properties' variation with regard to the material's temperature. In particular, specific heats tend to decrease at lower temperatures. In order to take into account these changes, the cool-down was broken into steps of temperature change, allowing use of a certain property value for each temperature interval. This calculation was done for a number of values for two key variables. First, the exit temperature of the helium gas was altered. Second, this value was held constant and the flow rate of the helium was varied.

## RESULTS

## Cooling of the Nitrogen Shield

Using Equation 2, we can estimate that the vacuum vessel, composed entirely of copper and weighing 39 pounds, will require $1,282 \mathrm{~kJ}$ of energy removal to cool to 77 K . The latent heat and enthalpy gain of liquid nitrogen vaporizing and heating back to room temperature can provide 432.3 kJ per kg of $\mathrm{N}_{2}$. Thus, $\frac{1,282 \mathrm{~kJ}}{432.3 \frac{k J}{k g_{N_{2}}}}=2.97 \mathrm{~kg}$ of $\mathrm{N}_{2}$ will be needed. With a conservative flow rate of 10 gaseous liters per minute, this would equate to 3.95 hours of cooling. A pump rate of 60 gaseous liters per minute reduces this cooling time to only 39.5 minutes.

With the estimated heat leak into the copper shield of 20 W , the cooling time required increased to 5.06 hours at 10 gaseous liters per minute and 41.0 minutes for 60 gaseous liters per minute.

## Warming the Nitrogen Shield

Solving Equation 3 for $\frac{\dot{Q}}{A}$, it is calculated that the vessel can only absorb $0.384 \mathrm{~W} / m^{2}$ through radiation. For every second that goes by, the shield can gain 0.384 Joules of heat for each square meter of its surface area. This heat gain is minuscule, especially when compared to the heat required to warm from 77 K to $300 \mathrm{~K}(1,282 \mathrm{~kJ}$, from the left hand side of Eqn. 1). The nitrogen shield will also gain heat through conduction through its supports and the various leads and pipes into the system, though no calculations were done in this study to estimate this heat flow.

## Cooling of the Magnet

Using Equation 4, it was determined how long it will take the magnet to traverse intervals of temperature. In Figure 5, the estimated amount of time needed to reach a temperature
was plotted for a number of different helium flow rates. The total amount of time to reach cool-down clearly depended on this flow rate, ranging from 5.95 hours for 200 gaseous liters per minute all the way up to 119 hours for 10 gaseous liters per minute.

Figure 6 was generated by varying the temperature at which the helium exits the system after vaporizing. A constant flow rate of 60 liters per minute (gaseous) was used. We would like the helium to heat all the way up to room temperature, sucking as much heat as possible away from the magnet. In this case, the magnet would take 19.8 hours to cool to 4.2 K . If the helium leaves at only 5 K , it would take nearly 50 days to cool. These results are summarized in Tables 1-3.

## DISCUSSION AND CONCLUSIONS

## Cooling of the Nitrogen Shield and Magnet

The results obtained from the simple energy balance are certainly logical, but it is difficult to determine whether or not they are in fact accurate without some sort of experimental verification. One may expect that the magnet, with significantly more mass and a required temperature of 4.2 K , would take much longer to cool than the nitrogen shield. As anticipated, the results show that magnet will indeed take a much longer time to cool down.

It is interesting to note that the two coolants have surprisingly different properties. Compared to nitrogen, helium has a greater ability to pull away enthalpic heat as it warms to room temperature. To go from a saturated vapor to room temperature, it can absorb 1541.8 $\mathrm{J} / \mathrm{g}$, compared to nitrogen's $233.4 \mathrm{~J} / \mathrm{g}$. On the other hand, the helium takes very little energy away as it changes phase (only $20.7 \mathrm{~J} / \mathrm{g}$, compared to nitrogen's $198.9 \mathrm{~J} / \mathrm{g}$ ). [7]

It is clear that higher mass flow rates and higher fluid exiting temperatures mean a significant decrease in the amount of time necessary for cooling. The results obtained are expected and logical. They are also quite useful, as they provide us with an idea of what
types of parameters will be needed to reach cool-down within a certain timeframe.
The graphs of the magnet's temperature against time reveal a key point about the cooling process of the magnet. Initially, the magnet will be slow to cool down. However, as it cools down, its specific heat decreases, allowing it to cool down more rapidly. This is what causes the distinct downward concavity of the curves.

## Warming of the Nitrogen Shield

The thirty layers of superinsulation clearly impede the vessel's ability to warm back up, but they also keep the vessel from warming up when we want it cold. We would rather have the insulation then not for this reason. The vessel's heating rate will decrease further as it gets closer to room temperature, further slowing the warm-up process. At this rate, it could easily take days to heat up the system so that it could be worked on; a costly waste of time. It should be noted, however, that these calculations only include radiation effects. Conduction through the supports holding the shield in place, the leads, and the piping were not included.

## Conclusions

A simple energy balance method was used to calculate the amount of time necessary to cool down the ILC superconducting quadrupole for a number of difference flow rates and helium exit temperatures. The graphs of temperature against time confirm our beliefs about how the magnet will cool. Cooling will be slow initially, then pick up substantially around 100K, due to the decrease in specific heat at lower temperatures.

Further studies would definitely be beneficial to the question of the model's accuracy. Applying a finite difference method was attempted, but as of the time of writing, the results were inconclusive. Accuracy of the model could be tested using a small, isolated experimental setup. By using $\mathrm{LN}_{2}$ to cool a much smaller piece of material and monitoring its
temperature using thermocouples, we could easily determine whether or not the model used was appropriate.

## ACKNOWLEDGMENTS

Special thanks to John Weisend, EunJoo Thompson, and Steve St. Lorant for their expertise and aid provided through the research. In addition, I'd like to thank the U.S. Department of Energy, Office of Science for providing the opportunity to work at SLAC this summer.

## APPENDIX 1: THE ASME PRESSURE VESSEL CODES

A secondary objective for my research this summer was to ensure that the vacuum and helium vessels meet the pressure vessel codes put forth by the American Society of Mechanical Engineers (ASME). The ASME codes provide a framework of calculations to ensure that vessels which are under pressure (be it external or internal) have sufficiently safe thickness, stiffness, axial strength, and reinforcement.

## Materials and Methods

The American Society of Mechanical Engineers requires that all designed vessels under pressure meet its minimum safety requirements. In order to conduct the experiments, we had to show that both the vacuum and helium vessels were safe. The housings were treated separately, as different codes exist depending on whether the vessel is facing internal or external pressure. The codes were explicit in their direction, and were mostly straightforward.

The vacuum vessel was considered first. Because the inside of the tank is a vacuum, the codes for pressure vessels under external pressures were used (ASME Section VIII, Division 2, Part AD, Article D-3 codes were those being used). We had to first show that the walls of the cylindrical tank were thick enough to withstand the external pressure acting on it (atmospheric pressure), complying to code AD-310.1. The next requirement was to ensure that the flanges on each end of the vessel were sufficiently stiff to resist unwanted torques, meeting code AD-331. The axial compression code, AD-340, determines whether the vessel is compressed to a dangerous amount. Finally, we had to ensure that the opening for the top housing (see figure) was appropriately reinforced. The opening was treated as a large nozzle, which, due its size, fell under the special codes of UG-37. The only required internal pressure codes for the helium vessel were checking its wall thickness (AD-201) and the thickness of the endplates (AD-702) [5].

## Results

The first code checked was that of the vacuum vessel's thickness. This calculation revealed that the thickness used was adequate to an external pressure of up to 162 psi, much greater than the atmospheric pressure it will face. The second code proved that the flanges provide a moment of $0.507 \mathrm{in}^{4}$, much greater than the necessary moment of $0.020 \mathrm{in}^{4}$. Next, the vacuum vessel would be able to withstand $12,600 \mathrm{psi}$ of compressive stress. It is expect to face 300 psi at most. Finally, the large opening at the top requires $2.16 \mathrm{in}^{2}$ of reinforcement. The shell to opening wall shape itself provides $2.71 \mathrm{in}^{2}$ of support.

The thickness checks for the helium vessel showed that the thickness required was only 0.056 ", while 0.250 " is the actual thickness. The lateral endcaps must have a thickness of at least 0.552 " and the top endcap must have a thickness of 0.260 ". The actual thicknesses are $1.12 "$ and 0.375 ", respectively.

## Discussions and Conclusions

The calculations done for the ASME Pressure Vessel Codes clearly indicated that the vessels which house the magnet are more than safe in all the required ways. Their shell thickness, reinforcement rings, opening reinforcements, and endcap thicknesses all passed the requirements. Many of the dimensions of our vessels were, in fact, several times greater than that required. Considering this along with the inherent safety factors in the code, there is no doubt that the construction is sound. Pumping the outer vessel down to its vacuum state corroborated these findings: no problem of any kind occurred.

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## FIGURES



Figure 1: A schematic of the magnet, as viewed from the side.


Figure 2: A photograph of the magnet. Note the inner layer of epoxy, with the embedded superconducting wires, the four quarters that compose the iron yoke, and the outer aluminum compression ring.


Figure 3: A schematic of the helium vessel, as viewed from the side. The magnet sits inside. LHe is pumped into the vessel via the bottom fill line until the vessel is full, at which point the level is maintained using the top fill line.


Figure 4: A photograph of the helium vessel.


Figure 5: The magnet's calculated temperature in time, with varying helium flow rates with an exiting temperature of 300 K .


Figure 6: The magnet's calculated temperature in time, with varying helium exit temperatures at 60 gaseous liters per minute.

## TABLES

| He Exit Temperature (K) | Time for Magnet to Reach 4.2K (hours) |
| :---: | :---: |
| 300 | 59.34 |
| 260 | 68.44 |
| 220 | 80.83 |
| 140 | 126.71 |
| 80 | 220.75 |
| 40 | 437.30 |

Table 1: Cooling times for a number of different helium exit temperatures for a gaseous helium flow rate of $20 \mathrm{~L} / \mathrm{min}$.

| He Exit Temperature (K) | Time for Magnet to Reach 4.2K (hours) |
| :---: | :---: |
| 300 | 19.78 |
| 260 | 22.81 |
| 220 | 26.94 |
| 140 | 42.24 |
| 80 | 273.58 |
| 40 | 145.77 |

Table 2: Cooling times for a number of different helium exit temperatures for a gaseous helium flow rate of $60 \mathrm{~L} / \mathrm{min}$.

| He Exit Temperature (K) | Time for Magnet to Reach 4.2K (hours) |
| :---: | :---: |
| 300 | 8.48 |
| 260 | 9.78 |
| 220 | 11.55 |
| 140 | 18.10 |
| 80 | 31.54 |
| 40 | 62.47 |

Table 3: Cooling times for a number of different helium exit temperatures for a gaseous helium flow rate of $140 \mathrm{~L} / \mathrm{min}$.

# Search for Mechanically-Induced Grain Morphology Changes in Oxygen Free Electrolytic (OFE) Copper 

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August 18, 2006

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> Signature

Research Advisor:

> Signature

## Table of Contents

Abstract ..... iii.
Introduction ..... 1
Materials and Methods ..... 3
Results ..... 5
Discussion and Conclusions ..... 5
Acknowledgements ..... 7
References ..... 8
Figures ..... 9


#### Abstract

Search for Mechanically-Induced Grain Morphology Changes in Oxygen Free Electrolytic (OFE) Copper. JENNIFER E. SANDERS (Westminster College, Fulton, MO 65251) ROBERT KIRBY (Stanford Linear Accelerator Center, Menlo Park, CA, 94025).

The deformation of the microscopic, pure metal grains ( 0.1 to $>1$ millimeter) in the copper cells of accelerator structures decreases the power handling capabilities of the structures. The extent of deformation caused by mechanical fabrication damage is the focus of this study. Scanning electron microscope (SEM) imaging of a bonded test stack of six accelerating cells at magnifications of 30, 100, 1000 were taken before simulated mechanical damage was done. After a $2^{\circ}-3^{\circ}$ twist was manually applied to the test stack, the cells were cut apart and SEM imaged separately at the same set magnifications (30, 100, and 1000), to examine any effects of the mechanical stress. Images of the cells after the twist were compared to the images of the stack end (cell 60) before the twist. Despite immense radial damage to the end cell from the process of twisting, SEM imaging showed no change in grain morphology from images taken before the damage: copper grains retained shape and the voids at the grain boundaries stay put. Likewise, the inner cells of the test stack showed similar grain consistency to that of the end cell before the twist was applied. Hence, there is no mechanical deformation observed on grains in the aperture disk, either for radial stress or for rotational stress. Furthermore, the high malleability of copper apparently absorbed stress and strain very well without deforming the grain structure in the surface.


## INTRODUCTION

The Stanford Linear Accelerator Center (SLAC) remains on the forefront of particle physics with tools such as the two-mile linear accelerator. The SLAC linear accelerator has enabled scientists to make profound, Nobel Prize-worthy discoveries in the field of particle physics. Higher frequency, higher energy accelerators such as the International Linear Collider (ILC) brighten the horizon of future studies in this area.

Accelerator designs for producing higher energy beams require detailed and precise measurements during design and operation. The developmental Next Linear Collider Test Accelerator (NLCTA) at SLAC found that accelerator structures meeting the ILC design requirements experience excessive radio frequency (RF) breakdown rates at the desired 65MV/m accelerating gradient. With a scanning electron microscope (SEM), the post-operation locations of RF breakdowns were determined by the presence of visible craters in the copper structure [1]. Studies on the effects of these breakdowns show that RF breakdown has become one of several critical factors defining the limit of the operating gradient of accelerating structures [2]. Therefore, development of structure designs, fabrication procedures, and processing techniques that minimize structure damage are vital to the advancement of accelerator science.

## Background

## Linear Accelerators

The NLCTA consisted of many copper vacuum aperture disks, grouped as chambers that were manufactured from 99.9\% pure Oxygen Free Electrolytic (OFE) copper. As electrons are accelerated in this copper structure, the chambers are exposed to an environment of radiation, electron and photon bombardment, and megawatts of RF power. Microwaves surge through the accelerator structure, creating oscillating electric and magnetic fields, forming an
electromagnetic wave that travels down the inside surface of the accelerator. The electrons pass through each chamber at the proper wavelength to receive the maximum push from the electric field in that cell. Though copper is a relatively low melting point metal, its good electrical conductivity keeps the power losses of the copper low, making it a choice metal for the traveling wave structure. In order for the particle to receive the optimum boost, the inner surface of the wave structure must resonate at the proper wavelength. A smooth, contaminate-free inner surface ensures the desired acceleration.

## Grain Deformation

The OFE copper is microscopically composed of pure metal grains from 0.1 to $>1 \mathrm{~mm}$ in diameter. Understanding and determining the sources of grain deformation on the inside surface of the structures is essential to accelerator science. Previous studies show that RF breakdown is overwhelmingly responsible for grain deformation in the copper surface. Occasionally, the wave structure absorbed the power, accompanied by a surge of current, which left visible craters on the structure [2]. Multiple breakdowns in the same area of a malleable metal such as copper may have caused these small grains to deform, altering the consistency of the metal.

However, during the mechanical fabrication stage of autopsying NLCTA cells, the accelerator structure experienced a small rotational twist. The cutting tool, that separated cells, caught in the metal, jumped, and twisted the entire bonded stack of cells. The extent of grain deformation, if any, caused by this rotational damage to the structure is undetermined.

This paper addresses mechanical fabrication as a possible source of grain deformation, which may have contributed to the limited capability of the test accelerator. The mechanical fabrication damage simulated by manually twisting a bonded stack of accelerating cells has been examined and imaged by SEM for grain deformation. We are particularly interested in the grain
structure of the cell planar iris, within several millimeters of the central aperture, where the electric field is highest and most breakdowns occur and deformed grains are formed. The irises are 2 mm thick and the overall thickness is 10 mm (Figure 1).

## MATERIALS AND METHODS

Six OFE copper cells numbered 60 through 65 were bonded as a small test stack for this study (Figure 1). These cells are of the type used for fabricating the accelerator structure of the NLCTA, but for various reasons were not used for that purpose. In an accelerator structure, cell numbers reference cell location within the larger accelerator structure. This study uses the numbers solely for identification and comparison purposes. The individual cells were from a lot of cells rejected for previous use because of incidental handling artifacts, e.g. scratches and dents.

Each individual cell went through the annealing furnace and chemical cleaning before being diffusion bonded at $1015-1020^{\circ} \mathrm{C}$ for an hour. Chemical etching on individual cells, lasting 60 seconds, effectively removed unwanted debris from the surface of the sample before bonding while the hydrogen furnace removes oxide from the surface area between the cells (which encourages atomic inter-diffusion between mating cell surfaces during the very high temperature bonding). After bonding, the stack of accelerating cells was vacuum-baked (to remove the excess hydrogen from the copper bulk) and then sealed in $\mathrm{N}_{2}$ to maintain the clean surface. The bonded stack of accelerating cells measures approximately 52 mm in length with cell 60 on the bottom of the stack, the recessed cup down (Figure 2).

For surface characterization before the mechanical damage, images of cells 65 and 60 (top and bottom) of the stack were taken with the SEM in magnifications of 30, 100, and 1000.

At these magnifications and a working distance of 15 mm (millimeters), the radial distance from the iris of the cell is easily observed and measured on the orders of 10,100 , and $1000 \mu \mathrm{~m}$. Characteristic surface images of at least three different areas on the cell were filed for use in later comparisons.

To simulate the rotational damage done to the NLCTA accelerator structure during mechanical fabrication, the test stack was placed in a lathe (Figure 3), anchored on one end, and manually twisted $1.5^{\circ}$ from the free end, severely damaging both end cells held by the lathe. The degree of twist was measured by the displacement of the number on the bottom cell from the centered number of the anchored cell. The rotated cell was displaced 1.25 mm -the desired amount of twist $\left(2^{\circ}-3^{\circ}\right)$.

To analyze the effect of the twist on each individual cell, the stack was cut apart. Fine machining smoothly shaved away as little as $25 \mu \mathrm{~m}$ per rotation until the wall around the recessed area was thin enough to tear away the iris. The iris of each cell was placed in a separate container labeled with the cell number. A small dot was also placed on the flat side of the iris of each cell to identify the accelerator beam out side, distinguishing one side from the other.

Imaging of cells 60 through 64 was done in the SEM with the set magnifications of 30 , 100, and 1000. Characteristic images of multiple locations on the surface of the cells are analyzed for grain deformation at a resolution of $0.1,1$, and $10 \mu \mathrm{~m}$ and compared to the images taken of cell 60, recessed end, before the twist. The comparisons of the images taken before and after the twist provide the data for a correlation between mechanical fabrication damage and grain deformation.


#### Abstract

RESULTS SEM imaging was done on cell 60 (recessed end) of the bonded stack before the manual twist and cells 60 through 64 (recessed end) after the manual twisting of the test stack. Images of cell 60 before the twist generally appeared as in Figure 4: many grains varying in size, shape, and brightness. Figure 5 shows an image of the same location on the cell after the twisting. Though cell 60 underwent enormous exterior damage during twisting, comparisons with the images of this cell (Figure 4) taken before twisting at each magnification (30, 100, and 1000), show similarity in appearance and grain consistency.

Cells $61-64$ were examined for changed morphology due to the manual twisting of the test stack. Figure 6 and Figure 7 show images of the grains in cells $61-64$ on the scale of 1000 $\mu \mathrm{m}$ and $100 \mu \mathrm{~m}$. The grain morphology is comparatively similar to the grains of cell 60 in which changes were not seen, even after extreme surface pressure. At the highest magnification used in examining the cells (1000X), multiple grains are observed to have high-angle grain boundaries, as in Figure 8. This type of boundary effects grains of different sizes, shapes and brightness throughout cells 61 through 64. Although the high-angle boundaries vary in severity, the deformation is only seen at the magnification of 1000 (10 $\mu \mathrm{m}$ scale) and therefore is not related to the macroscopic deformation searched for in this study.


## DISCUSSION AND CONCLUSIONS

Because multiple occurrences of RF breakdown lead to grain deformation in the surface of OFE copper vacuum aperture disks, RF breakdown performance has become one of several critical factors limiting the capabilities of higher frequency accelerators. As a result great efforts have been made in characterizing, understanding, and reducing RF breakdowns [1]. However,
searching for other possible sources of grain deformation is important for producing high energy, efficient accelerators.

This study focused on the SEM examination of five OFE copper cells after simulated mechanical fabrication damage, in order to correlate mechanical fabrication damage with grain morphology changes in the cells. SEM imaging of cell 60, before and after the compression of the lathe, showed that radial deformation of the cell does not induce changes in the morphology of the cell's grains within 2 mm of the cell's iris (the area affecting the beam acceleration). Figure 4 and Figure 5 prominently show that grains remained the same, and furthermore, that the voids (dark spots) along the grain boundaries were not altered—evidence that the grains did not undergo any deformation.

Cells 61 - 64 lack evidence of rotational deformation from the twist performed on the stack. Figures 6 and 7 of the cells at magnifications of 30 and 100 resemble the previously discussed figures of cell 60 (Figures 4, 5).

The presence of high-angle grain boundaries ( $10 \mu \mathrm{~m}$ ) results from the recrystallization process of copper after it was put through the furnace. When the copper cells are heated in the furnace, grains within the surface of the cell melt and merge together, forming bigger grains with smooth boundaries. During the cooling process, the grains recrystallize in this new formation nicely aligned within the copper structure. However, some grains do not merge with others or form compatible grain boundaries. This type of uncompromising behavior within the cell's surface results in high-angle grain boundaries. These high-angle grain boundaries are common in metallurgy and do not result from rotational deformation.

Therefore, because changes in grain morphology were not induced by either radial or rotational damage of a small degree, machine fabrication damage of this kind is uncorrelated
with grain deformation within these cells. Furthermore, this study revealed the extensive ability of copper to absorb great stress and strain, as evidenced by the unchanged composition of the end cell (60) after the intense radial compression of the cell.

For future study of the effects of mechanical fabrication damage on the grain morphology of OFE copper, imaging of each individual cell prior to bonding the cells into a stack would help to diagnose grain deformation after twist or RF power. Also, the use of high-quality cells acceptable for accelerator use would confirm the results of this study.

## ACKNOWLEDGEMENTS

This research was conducted at the Stanford Linear Accelerator Center in Stanford, California. I thank the United States Department of Energy, Office of Science for giving me the opportunity to participate in the SULI program, acquiring amazing educational experience necessary for a future in science. The greatest appreciation goes to my mentor Robert Kirby for his excellent knowledge of the subject matter, and his desire to show me every aspect of lab work, as well as Dr. Frederic LePimpec for conceiving the project. I also thank Gerard Collet, who performed the manual twist and cutting of the cells, the other members of the SLAC Surface and Materials Science, and the Klystron Department (Chris Pearson and John Van Pelt) for providing the bonded structure.

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## FIGURES



Figure 1 Flat side and recessed side of an OFE copper accelerator structure cell.


Figure 2 OFE Copper small test stack, cell numbers 60 through 65, used for this study before the manual twisting. The bottom of the stack, cell 60, shows the recessed cup of the cell. Notice the cell numbers and lower holes are perfectly aligned.


Figure 3 OFE Copper small test stack, cell numbers 60 through 65, locked in the lathe after the manual twisting. Notice the slight misalignment of the cell numbers as well as the lower holes.


Figure 4 SEM image of copper grains in surface of cell 60 at magnification of 30 X before twisting damage.


Figure 5 SEM image of copper grains in surface of cell 60 at magnification of 30 X after twisting damage.


Figure 6 SEM images of copper grains in the surface of cells 61 - 64 at magnification of 30 after twisting. There are no signs of grain deformation.


Figure 7 SEM images of copper grains in surface of cells 61-64 at magnification of 100 after twisting. There are no signs of grain deformation.


Figure 8 SEM image of high-angle grain boundary in cell 61at magnification of 1000 after twisting.

# Host Galaxies of X-shaped Radio Sources 

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August 25, 2006

Prepared in partial fulfillment of the requirements of the Office of Science, Department of Energy's Science Undergraduate Laboratory Internship under the direction of Chi C. Cheung at the Kavli Institute for Particle Astrophysics and Cosmology, Stanford Linear Accelerator Center.

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## TABLE OF CONTENTS

Abstract ..... ii
Introduction ..... 1
Materials and Methods ..... 3
Results ..... 4
Discussion and Conclusions ..... 5
Acknowledgments ..... 7
References ..... 7


#### Abstract

Host Galaxies of X-shaped Radio Sources. ALESSONDRA SPRINGMANN (Wellesley College, Wellesley, MA 02481) CHI C. CHEUNG (Kavli Institute for Particle Astrophysics and Cosmology, Stanford Linear Accelerator Center, Menlo Park, CA 94025).

The majority of radiation from galaxies containing active galactic nuclei (AGNs) is emitted not by the stars composing the galaxy, but from an active source at the galactic center, most likely a supermassive black hole. Of particular interest are radio galaxies, the active galaxies emitting much of their radiation at radio wavelengths. Within each radio galaxy, an AGN powers a pair of collimated jets of relativistic particles, forming a pair of giant lobes at the end of the jets and thus giving a characterisitic double-lobed appearance. A particular class of radio galaxies have an "X"-shaped morphology: in these, two pairs of lobes appear to originate from the galactic center, producing a distinctive X-shape. Two main mechanisms have been proposed to explain the X -shape morphology: one being through the merger of a binary supermassive black hole system and the second being that the radio jets are expanding into an asymmetric medium. By analyzing radio host galaxy shapes, we probe the distribution of the stellar mass to compare the differing model expectations regarding the distribution of the surrounding gas and stellar material about the AGN.


## INTRODUCTION

Among the largest and most prevalent structures in the Universe are extragalactic radio sources, emitting strongly in the radio portion of the spectrum. Thousands of these objects exist, ranging in size from approximately 50 kiloparsecs across (approximately 150,000 light-years) to 100 kiloparsecs (300 light-years). These radio sources are composed of relativistic plasma jets traveling at high relativistic speeds, and emit synchrotron radiation (relativistic electrons moving through weak magnetic fields). Extragalactic radio sources contain a central host galaxy, from which two jets are emitted. As the jets interact with the surrounding intergalactic medium, a pair of giant radio lobes form. Figure 1 shows Cygnus A, a typical extragalactic radio source approximately 100 kiloparsecs across, which exhibits a central host galaxy (blue), collimated jets, and radio lobes (both red).

In addition to being large, coherent structures, extragalactic radio sources are also highly energetic. The energy output of typical extragalactic radio sources is $10^{44} \mathrm{ergs} /$ second, with some sources having energies of up to $10^{59} \mathrm{ergs} / \mathrm{second}$. (Our Sun, in comparison, has a luminosity of $10^{33} \mathrm{ergs} /$ second, making it $10^{11}$ orders of magnitude less energetic than Cygnus A.) The majority of radio galaxies emit the majority of their radiation not from the stars, gas, and dust composing the galaxy, but from the active source at the center, an active galactic nuclei (AGN), widely believed to be a supermassive black hole [1].

Thousands of these extragalactic radio sources resemble the canonical object Cygnus A in that they posses one pair of radio jets. However, approximately a dozen radio galaxies have two sets of jets emitting from the central supermassive black hole, forming a distinctive "X"-shape [2]. Over the past three decades, the number of known sources possessing the X-shaped morphology has grown from a dozen to over a hundred candidates, allowing for more detailed studies of these objects, particularly regarding their shape and origin. Figures 2 and 3 show double radio sources $\mathrm{J} 1513+2607$ and $\mathrm{J} 1606+0000$, which display a distinctive

X-shaped morphology.
Astronomers propose that this distinct shape may be the result of a recent collision or merger between two supermassive black holes, which can produce the extra set of jets and lobes. Another explanation is that the main jets expanded into an asymmetric medium, which we probe by studying the host galaxy. Hydrodynamical simulations by [3] (Figure 4) show that as a jet, aligned parallel to the semi-major axis of an elliptical galaxy ${ }^{1}$, propagates into the surrounding gas distribution, two major jets form, and smaller wings will form orthogonal to the major jets, producing X -shaped radio lobes.

From the x-ray observations performed by [4] of the gas surrounding elliptical galaxies, we know that stellar light is an efficient way of probing gas distribution, as the distribution of gas around a host galaxy follows the distribution of stars in the galaxy. Thus, a galaxy with an elliptical distribution of stars will have an elliptical distribution of surrounding gas. Wing formation is most pronounced in elliptical galaxies, with the main set of jets forming parallel to the major axis of the galaxy. Studying a small set of host galaxies, [3] found that more elliptical galaxies have a secondary set of "wings", which align orthogonal to the semi-major axis of the host galaxy, as shown in their simulations and in Figure 6.

In this paper, we investigate the ellipticity of the galaxies that play host to the Xshaped sources, in order to determine if galaxies with more elliptical distributions of gas have X-shaped jets. Using the ellipse package for Image Reduction and Analysis Facility (IRAF) ${ }^{2}$ to model the elliptically-shaped isophotes, or regions of equal brightness, of the galaxies, we determined the ellipticity and extent of the host galaxies and compared these to radio galaxy morphology, and therefore tested the results of previous studies (such as those carried out by [3]) with a larger sample of X-shaped radio sources.

[^0]
## MATERIALS AND METHODS

Our data of 19 host galaxies of X-shaped extragalactic radio sources were collected by the Sloan Digitized Sky Survey (SDSS). The images are 56-second exposures taken in the $r$-band filter, which has a central wavelength of 6280 ångstroms. All objects imaged are 18th magnitude ${ }^{3}$ or brighter in the $r$-band, as dimmer objects would otherwise not be sufficiently resolved by the SDSS charge-coupled device (CCD). The pixel scale of the SDSS CCD is 0.4 arcseconds and the seeing for each image is approximately one arcsecond. A sample source image, the host galaxy of source J0813+4347, is shown in Figure 7.

Elliptical isophotes, or regions of equal brightness, of these host galaxies were fitted by the ellipse routine of the Space Telescope Science Data Analysis System (STS-DAS) ${ }^{4}$ isophote package for IRAF.

The isophote fitting methods are described by [5]: the center and length of the outermost elliptical isophote's semi-major axis are specified by the user, then the software plots successively smaller isophotes on the image, as seen in Figure 8. Information pertaining to the isophote plots, such as the semi-major axis of the isophote in pixels, ellipticity of the isophote ${ }^{5}$, and position angle of the isophote relative to north in the image are written to a table.

A routine called bmodel then converts this table to a model of relative isophotal intensities and sizes, which can then be subtracted from the original image to judge the goodness of the isophote fits. Figure 9 shows the isophote model subtracted from the background image and that the isophote model matches the intensity of the host galaxy, leaving minimal residual background on the original image.

[^1]The position angles of the radio lobes and wings of the actual X-shaped sources were measured from data taken by the Very Large Array (VLA) ${ }^{6}$. The difference between the position angles of the host galaxies' semi-major axes and the position angles of the radio wings of the X-shaped sources are shown in Table 1 with the values for the ellipticities of host galaxies, calculated from the isophote fits calculated from the ellipse routine.

## RESULTS

Galaxy parameters (position angle of the main set of radio jets, position angle of the radio wings, position angle of the host galaxy in the optical, ellipticity of the host galaxy, and offset between the radio wing position angle and the optical host galaxy position angle) were measured for four known X-shaped sources from the literature [2] and five new objects found by Cheung with a distinct X-shape [2].

The distribution of host galaxy ellipticities for our 19 sources (in blue) is compared to a sample of "normal" (not X-shaped) host galaxies of extragalactic radio sources analyzed by [3] (white) is shown in Figure 10. Some of these host galaxies are highly elliptical; however, approximately eight of these objects have ellipticities consistent with the host galaxy being circular. Capetti found that the host galaxies of X-shaped sources tended to be highly elliptical [3], which is contrary to our finding of the host galaxies of these X-shaped objects ranging from being circular to highly elliptical. It appears that the host galaxy need not be highly elliptical to cause wing formation in these eight cases.

Although the ellipticities of these host galaxies show no specific trend toward either high or low ellipticity, the offset between the host galaxy optical semi-major axis position and that of the radio wings tends to be approximately orthogonal for six out of nine objects for which exist VLA observations, as shown in Figure 11.

With the position angles of the radio lobes and wings taken from the VLA data in

[^2]Table 1, there appears to be little connection between the ellipticity of the host galaxy and the presence of radio wings orthogonal to the semi-major axis of the host galaxy. This is evidenced by objects J0805+2409, J0831+3219, and J1614+2817, with low ellipticities (less than 0.12 ) and an approximately orthogonal offset between the radio wings and optical semi-major axis of the host galaxy.

However, we can only measure host galaxy position angles if they are highly elliptical (for ellipticities greater than 0.12), which produces low-confidence measurements of the isophotal position angles of the semi-major axes of the host galaxies.

Comparing the host galaxy position angle to the wing position angle, we find that the difference in these angles are clustered around $90^{\circ}$, or that the position angles are orthogonal, consistent with the findings of [3]. However, unlike [3], we find that galaxies with circular isophotes play host to X -shaped radio sources.

## DISCUSSION AND CONCLUSIONS

We measured host galaxy ellipticities from 19 sources and these are plotted in Figure 10. Some of these host galaxies are highly elliptical, with ellipticity values of over 0.12 ; however, four of these objects have ellipticities consistent with being circular. We compared the ellipticities to the comparison sample of normal radio galaxies from [3] and the distributions are indistinguishable, contrary to the findings of [3]. Simulations performed by [3] that an elliptical distribution of gas about a host galaxy produces the main lobes and auxiliary wings seen in X-shaped sources. The host galaxy need not be highly elliptical to cause wing formation in extragalactic radio sources.

X-ray observations performed by [4] of 3C 403, an X-shaped source, demonstrating that the optical position angle of the host galaxy follows the X-ray gas distribution. Therefore, in at least one X-shaped source, we know that the gas follows the star distribution of
the galaxy, and thus if the galaxy appears elliptical in the optical band, it is also most likely elliptical in its gas distribution. According to [3], if the stellar light follows the distribution of gas around the galaxy, is elliptical, and is on a scale much larger than that of the host, comparable to the size of the X-shaped lobes and wings, then the double morphology of the X-shaped radio galaxies will form as the main set of jets expand into the surrounding gas.

Although the model proposed by [3] does not account for circular host galaxies, a way to resolve this discrepancy is to consider the orientation effects of the host galaxy. A galaxy with the form of an ellipsoid viewer from its most circular side will appear to have circular isophotes as a consequence of the observer's position. However, it is unlikely that galaxy having the shape of a spheroid (an ellipsoid with two axes equal in length) would have a spherical side facing Earth. It is more likely that, although our results for J0831+3219 agree with deeper observations by [6], the data from the Sloan Digital Sky Survey is "shallow", or that the objects were not sufficiently exposed to obtain a high enough signal to noise ration in order to resolve the elliptical isophotal structure of these host galaxies.

We compared our measurements with much deeper data taken at longer exposures for one well-studied, low-ellipticity object, J0831+3219 [6]. As our values for ellipticity and position angle of the host galaxy are consistent with Ulrich's, this demonstrates that the Sloan Digital Sky Survey data is valid and comparable to "deeper", or longer-exposure observations.

The model proposed by [3] might have difficulty explaining the circular hosts of these X-shaped sources, however, it should not be discounted. There are a number of papers, including [3], which describe hydrodynamical situations that lead to X-shaped source formation and are supported by not only with data but by simulations. Other models exist that propose that the formation of secondary wings in extragalactic radio sources due to the realignment of the central supermassive black hole of a host galaxy, due perhaps to galactic mergers, but they lack significant simulations or data to reinforce their predictions. In order
to verify whether the Capetti or black hole realignment model most accurately describes the creation of X-shaped extragalactic radio sources and further understand the formation of these objects, more simulations of galactic mergers should be performed, in addition to deeper observations being made of both the host galaxies and X-shaped sources.

## ACKNOWLEDGMENTS

This research was conducted at the Kavli Institute for Particle Astrophysics and Cosmology at the Stanford Linear Accelerator Center. I thank the U. S. Department of Energy, Office of Science and Michael Woods for the opportunity to participate in the SULI program and for the tremendous learning and research experience. Immense thanks are due to my mentor Teddy Cheung for his knowledge of extragalactic radio astronomy, patience, persistence, and sense of humor. I also thank Alexandra Rahlin for providing invaluable help with Matlab scripting and $\mathrm{EA}_{\mathrm{E}} \mathrm{X}$ formatting. I am grateful to the faculty and staff of KIPAC, especially Stuart Marshall and Grzegorz Madejski, for hosting me this summer and generously providing us students with a wealth of resources and encouragement.

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## TABLES

Table 1: Object name (in J2000 coordinates), the position angle of the main set of radio jets, the position angle of the radio wings, the position angle of the host galaxy in the optical, the ellipticity of the host galaxy from the optical images, and the offset between the radio wing position angle and the optical host galaxy position angle are shown.

| Object Name | Radio Lobe PA | Radio Wing PA | Optical PA | Optical Ellipticity | Offset |
| :---: | :---: | :---: | :---: | :---: | :---: |
| J0805+2409 | 123 | 58 | 140 | 0.013 | 82 |
| J0813+4347 | 105 | 140 | 40 | 0.137 | 100 |
| J0831+3219 | 60 | 177 | 76 | 0.085 | 101 |
| J1005+1154 | 170 | 125 | 102 | 0.102 | 23 |
| J1020+4831 | 170 | 125 | 134 | 0.156 | 9 |
| J1130+0058 | 100 | 10 | 35 | 0.249 | 25 |
| J1513+2607 | 12 | 130 | 33 | 0.341 | 97 |
| J1606+0000 | 55 | 23 | 113 | 0.418 | 90 |
| J1614+2817 | 106 | 175 | 82 | 0.104 | 93 |

## FIGURES



Figure 1: Extragalactic radio source Cygnus A. The host galaxy is imaged in the optical band shown in blue at the center, while the radio jets and lobes are shown in red. The total size of Cygnus A is 100 kiloparsecs across, approximately 300,000 light-years. The optical image of the host galaxy is courtesy of the Spitzer Space Telescope and the radio image was taken with the Very Large Array, courtesy of the National Radio Astronomy Observatory/Associated Universities, Inc.


Figure 2: J1513+2607, an extragalactic radio source with two pairs of jets, from [7].


Figure 3: J1606+0000 in the radio band, showing two sets of jets in a winged shape, from [2].


Figure 4: Hydrodynamical simulations performed by [3]. These numerical simulations show density images representing the evolution of the radio-source in the stratified medium of the host galaxy. The top panels refer to the case when the jet is oriented parallel to the major axis of the gas distribution, while the lower panels to the case when the jets is parallel to the minor axis. The white represents the distribution of gas about the host galaxy, while the dark gray represents the expanding radio jets.


Figure 5: A model of an elliptical galaxy as a three-dimensional ellipse, or ellipsoid. When viewed from Earth it appears to be a flat ellipse.


Figure 6: Superposition of the host galaxy shape (not in scale) onto the radio image maps for X-shaped source 3C 223.1. Superposition by [3], with radio maps from [8].


Figure 7: Detail of J0813+4347, an elliptical host galaxy imaged in the $r$-band by the SDSS telescope.


Figure 8: Isophotes fitted to J0813+4347 by the ellipse routine of the SDS-DAS package for IRAF.


Figure 9: The J0813+4347 image with the isophote model subtracted from the data image. The original galaxy has been completely removed, except for the bright point at the center (the host galaxy AGN).


Figure 10: A histogram of the ellipticities of the host galaxies of X-shaped sources. The white histogram are the "control" objects from [3] and the blue histogram are the host galaxies of X-shaped radio sources.


Figure 11: A histogram of the position angle offsets between the semi-major axis of the host galaxies and radio wings of the X-shaped radio sources.

# Determining Micromechanical Strain in Nitinol 

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August 18, 2006

Prepared in partial fulfillment of the requirements of the Office of Science, U.S. Department of Energy Science Undergraduate Laboratory Internship (SULI) Program under the direction of Dr. Apurva Mehta in the Stanford Synchrotron Radiation Laboratory (SSRL) at the Stanford Linear Accelerator Center (SLAC).

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## Table of Contents

Abstract ..... iii
Introduction ..... 1
Materials and Methods ..... 5
Results and Discussion ..... 6
Conclusions ..... 10
Acknowledgements ..... 11
References ..... 11
Tables ..... 12
Figures ..... 13

Abstract<br>Determining Micromechanical Strain in Nitinol. MATTHEW STRASBERG (Cornell University, Ithaca, NY 14853) ERICH OWENS (Albion College, Albion, MI 49224) APURVA MEHTA (Stanford Linear Accelerator Center, Menlo Park, CA 94025) SAMUEL WEBB (Stanford Linear Accelerator Center, Menlo Park, CA 94025)

Nitinol is a superelastic alloy made of equal parts nickel and titanium. Due to its unique shape memory properties, nitinol is used to make medical stents, lifesaving devices used to allow blood flow in occluded arteries. Micromechanical models and even nitinol-specific finite element analysis (FEA) software are insufficient for unerringly predicting fatigue and resultant failure. Due to the sensitive nature of its application, a better understanding of nitinol on a granular scale is being pursued through X-ray diffraction techniques at the Stanford Synchrotron Radiation Laboratory (SSRL) at the Stanford Linear Accelerator Center (SLAC). Through analysis of powder diffraction patterns of nitinol under increasing tensile loads, localized strain can be calculated. We compare these results with micromechanical predictions in order to advance nitinol-relevant FEA tools. From this we hope to gain a greater understanding of how nitinol fatigues under multi-axial loads.

## INTRODUCTION

## Nitinol

A biomedical stent is a lifesaving device used to allow blood flow in an occluded artery. Most stents produced are made of nitinol, shape memory alloy that can be drastically deformed and then heated back to its original shape. This allows for the stent to be compacted for easier insertion into an artery and then expanded, restoring proper blood flow. Once placed in a patient, the stent will expand and contract with each heartbeat. For the typical patient, these stents will undergo some half a billion cycles in the ten year lifetime required by the FDA.

As a result, designing against fatigue is a pressing concern in this industry. Current designs implement micromechanical models and nitinol-specific finite element analysis (FEA) to predict fatigue characteristics. However, stents are failing earlier than anticipated. This deviation can be accounted for by the lack of knowledge of how residual stress accumulates in nitinol. Continuum mechanics, the current model of analyzing stress and strain, is based in the macroscopic scale where elastic and plastic deformations are merely terms to relate the quality of strain in a material. Thus a superelastic material is modeled in the same manner as any other material, just with different numerical constants (Young's Modulus, Poisson’s ratio, etc...). However, on the granular and atomic scales such deformations have tangible meanings. Atomically, elastic deformation corresponds to a stretching of bonds and plastic deformation refers to breaking of bonds. As a result, understanding the nanocrystalline structure of nitinol is crucial to understanding how loading translates into strain, thus causing fatigue.

## Diffraction

X-ray diffraction can be used to determine nanocrystalline structure utilizing Bragg's Angle principles and Laue's equations. Those truly interested in the theory and practical
derivations should seek an outside text on X-ray diffraction [1], but the basic principles will be discussed in the following. Using a plane-wave source with a wavelength smaller than the lattice spacing, the waves will reflect off the atoms and constructively interfere, Figure 1, if Bragg's equation is satisfied: $2 d \sin (\vartheta)=n \lambda$, where $d$ is the spacing between atomic planes, $\lambda$ is the wavelength, and $2 \theta$ is the supplementary angle between the incident wave and the reflected wave. Meaning the path difference of two waves is equal to some integer multiple of the wavelength. The inverse relation between d and $\theta$ implies the larger the spacing d the smaller the angle of reflection $\theta$. Defining Q as the vector denoting the change in momentum from the incident wave and reflected wave, then $\mathrm{Q}=(4 \pi \sin \theta) / \lambda$ and bisects the incident and reflected waves thus pointing along d . Figure 2 is the same geometry, just rotated $\theta$ as a matter of convenience. Note, the incident wave is normal to the sample and is deflected an angle $2 \theta$ as before. As mentioned the change in momentum vector, Q , bisects the angle between the incident wave and the reflected wave or is an angle $\theta$ from the surface plane of the sample. The angle between Q and the surface plane of the sample will be given the generic name $\omega$. This convention is used because for any sample there will be multiple d spacings and as a result multiple angles of deflection $\theta$, where d spacings are the distance between atomic planes. Thus, $\omega$ is used to just to track the position of the Q vector. Since this is a three dimensional system one more angle is needed to locate Q , that angle will be called $\chi$. Visualize $\chi$ as rotating the Q vector around the incident beam $I_{0}$ into the page while maintaining a constant $\omega$ with the surface plane. Physically, $\chi$ corresponds to different orientations of a d spacing thus the reflected beam can be envisioned as line down the surface of a cone with apex $2 \theta$. In order to extract a diffraction pattern from this configuration, an area detector is placed normal to the incident beam. The detector will intersect the reflected wave cone creating a ring, called a $\chi$ arc or $\chi$ ring,
in the diffraction pattern, shown in Figure 3. Recalling the inverse relation between d and $\theta$, the rings closer to the center of the pattern corresponded to the larger d spacings in the atomic structure. Accordingly, there will be a different ring for each d spacing, thus each $\omega$, as shown in Figure 3. In an unstrained case, such as Figure 4, the $\chi$ rings are circular, but as a load is introduced the rings change shape. In order to understand the effect loading has on a diffraction pattern for nitinol, let's first discuss the micromechanical processes in nitinol.

## Nitinol Micromechanics

There are four micromechanical processes in Nitinol: elastic deformation, phase transformation, twining/de-twining, and plastic deformation. Nitinol has two primary phases in the solid state that are both temperature and strain energy dependent: austenite and martensite. How to create nitinol in a certain phase for a certain temperature is a whole science in itself, but this experiment uses nitinol in the austenite phase at room temperature. Figure 4 is the pattern for the unstrained austenite state, which has concentric circular $\chi$ rings. As a load is introduced, the austenite begins to elastically deform which translates to reversibly stretching of atomic bonds. If the load, thus strain, is uniform in all directions, i.e. hydrostatic, then the $\chi$ rings will maintain their circular shapes but the radius of each ring will change. Due to the inverse relation of $d$ and $\theta$, if the sample is under compression the radii will increase corresponding to a decrease in d; conversely if the sample is under tension the radii will decrease corresponding to an increase in d. For non-hydrostatic forces, such as the uniaxial tension in this experiment, the $\chi$ rings become elliptical. As the load increases, while still in the range of elastic deformation, the rings become more eccentric. For analysis it is convenient to transform the diffraction pattern from a collection of rings to a series of lines. This is done by unfolding the rings in a program, Fit2D, using the cake function. Figure 5 shows three sample peaks at increasing levels of strain,
the vertical axis is $\chi$ varying from $-\pi$ to $+\pi$ and the horizontal axis is Q over an arbitrary range in $\mathrm{nm}^{-1}$. The unstrained caked peak is shown in the upper left corner of Figure 5, and is a vertical line. As strain is increased, the peak changes from a straight line to a double arch of increasing eccentricity. As strain increases, the intensity of the peak decreases and starts to disappear. The disappearance of a peak corresponds to the appearance of another peak indicating a phase transformation. Specifically, the austenite is transforming to martensite, which has a different atomic spacing hence the disappearing and appearing of peaks.

The scope of this paper only covers elastic deformation in austenite; however I will discuss the other the micromechanical processes in order to create a broader understanding of diffraction theory. Figure 6 shows nitinol in the martensite phase, the peak is the vertical orange and pink stripe. The variation in intensity within the peak, the purple spots on the first image, relate that there is a certain texture within the material. Although this starting texture was arbitrary, the bright spots do indicate there were more martensite unit cells oriented at $\chi$ zero and $\pi$ in that sample. Again, each successive image in Figure 6 corresponds to an increased level of strain. As strain is increased the texture progresses to a different configuration, one more favorable to the strain conditions. This texture is called the twined state and is recognized by the two distinct bright spots, or poles, on the caked image. Under an even greater strain as shown in the last row of Figure 6, the peak starts to widen and, although not obvious on this scale, starts to lower in intensity. These changes, increase in peak width and decrease in peak intensity, coincide with plastic deformation. Physically, the unit cell clusters are breaking apart shortening the coherence length within the sample. Thus, the intensities of each cluster have a summing effect rather than a multiplicative effect if the sample was still continuous.

Using diffraction images of austenite under elastic deformation, this paper will discuss and develop techniques for finding strain on the micro-scale. This will be done in Q-space and relate that to the sample geometry. Through analysis of this strain, the effect of macro-strain on the material will become more relevant aiding in design against fatigue.

## MATERIALS AND METHODS

## Diffraction

The diffraction was performed by Apurva Mehta and David Bronfenbrenner at SSRL. The laboratory was setup for routine powder diffraction of a thin strip specimen with a $0.97350 \AA$ beam directly incident on the sample. A thin film of nitinol was placed in a constant strain device and elongated at set increments until 470 microns of elongation. Figure 7 shows the geometry of the strain device inducing; the strain induced by this device will be referred to as macro-strain. Due to the precision of the strain inducing mechanism, the macro-strain will only be considered in relative terms.

## Data processing

Fit2D, a freeware program http://www.esrf.fr/computing/scientific/FIT2D, was used to convert the raw data into a more usable form. For each pattern, each diffraction ring was isolated and "unfolded" into a linear form using the cake function (see Fit2D help file for information on the cake function). Figure 8 shows three diffraction patterns, three of fourteen in the data set, each at a different level of macro-strain. For each diffraction pattern three $\chi$ rings or peaks (in Miller indices hkl: 110, 200, 211) were caked in Fit2D as shown. These caked images were analyzed in 2DPeakFinder, which extracts the peak position, intensity, and width for every angle $\chi$. 2DPeakFinder is a Matlab script written by [2].

## RESULTS AND DISCUSSION

## Unstrained do

The question becomes, at what strain do these micromechanical processes occur? In order to find the strain locally we find the difference in the d spacings along a Q vector and the unstrained d spacing $\left(\mathrm{d}_{0}\right)$. To find $\mathrm{d}_{0}$ we must analyze the unstrained image. Looking at the caked images, the unstrained peak should be perfectly straight, recall circular ring to straight line and elliptical ring to arches. Practically this is a difficult thing to determine by eye using only the Fit2D images. Thus, a computational tool, a Matlab script, was developed by [2] to analyze the caked image and remove background intensity. This tool assumes a Gaussian shape for peak intensity and thus is able to determine the position of the peak in terms of Q and $\chi$, the width of the peak in Q, and the intensity for each caked image. Figure 9 shows the unstrained 110 peak plotted with Q as a function of $\chi$, which should be a straight line. Since the strain induced is uniaxial, the resulting change in the diffraction ring will be elliptical and thus create symmetric arches in the caked image. However, as shown in Figure 9 there is some variance which is not symmetrical and thus cannot be attributed to strain. It is not expressly stated, but to get the data in the form shown in Figure 9 the data has undergone two filtrations. First, the diffraction pattern was turned into a caked imaged in Q-space using Fit2D. Next, the relevant information from the caked image was extracted in Matlab. Both of these processes introduce some error because of the nature of their algorithms and account for the variance in the data. In order to locate the location of the unstrained peak in Q-space, the data was fit using a basic two element Fourier model with Q as a function of $\chi: \quad Q(\chi)=a_{0}+a_{1} \cos f \chi+b_{1} \sin f \chi \quad$ where $a_{0}, a_{1}, b_{1}$, and $f$ are all constants. Giving the unstrained Q location as $\left[a_{0}\right]$ and [the original data $-a_{0}$ ] as a calibrating factor to adjust for the error discussed above. The calibrating factor for the 110 peak
will be subtracted from each strained set of data for the 110 peak. This process is repeated for every unstrained peak $(110,200,211)$. Once knowing the location in Q for the unstrained peak, $\mathrm{d}_{0}$ can be found using the relation $d=2 \pi / Q$. This information is shown in Table 1.

## Strain Formulae

Knowing $\mathrm{d}_{0}$, the only other information needed to find strain along the Q vector is $\mathrm{d}_{\chi, \omega}$. The strained data undergoes the same filtrations, Fit2D and 2dPeakFinder, thus must utilize the calibration factor mentioned above. For the sake of clarity, we will only discuss the 110 peak and will provide the necessary definitions in Table 2. We will refer to $\mathrm{Q}_{\text {fit }}$ as the desired result for which all strain calculations will be done. $\mathrm{Q}_{\text {fit }}$ is the result of a weighted Fourier fit ( $\left.Q_{f i t}(\chi)=a_{0}+a_{1} \cos f \chi+b_{1} \sin f \chi\right)$. Using this type of fit assumes the deviation from the unstrained image is due to purely axial loading. The input of the Fourier fit is $\left(\mathrm{Q}_{\text {strain }}\right.$ - Calibrant) as a function of $\chi$ and refined by weighting each point by its Intensity. As discussed before, the Q vector, or specifically $\mathrm{Q}_{\mathrm{fit}}$, can be located using angles $\chi$ and $\omega$. Thus the strain is given as: $\varepsilon_{\chi, \omega}^{\prime}=\frac{d_{\chi, \omega}-d_{o}}{d_{o}}$, where $d_{\chi, \omega}=2 \pi / Q_{\text {fit }}$ and, since $\omega$ is the same as $\theta$ in this geometry $\omega=\sin ^{-1}\left(\frac{Q_{f \mathrm{t}} \lambda}{4 \pi}\right)$, where $\lambda$ is the wavelength of the incident X-ray. The strain along the Q vector can also be expressed in terms of the sample coordinate system, shown in Figure 10. Logically working backwards, if we assume the strain in the sample coordinate system is of the form of a second order, symmetric tensor having six unique elements then we can transform the sample strain into strain along Q . Accordingly, the strain along the Q vector will be:

$$
\varepsilon_{\chi, \omega}^{\prime}=a_{3 k} a_{3 j} \varepsilon_{j k} \quad a_{i j}=\left|\begin{array}{ccc}
\cos \omega & -\sin \omega \sin \chi & -\sin \omega \cos \chi \\
-\sin \chi \sin \omega & \cos \chi & -\sin \chi \cos \omega \\
\sin \omega & \sin \chi \cos \omega & \cos \omega \cos \chi
\end{array}\right|
$$

Where $\mathrm{a}_{\mathrm{ij}}$ is the transformation matrix between the two coordinate systems. Giving the strain

$$
\begin{aligned}
\varepsilon_{\chi, \omega}^{\prime}= & \left(\sin ^{2} \omega\right) \varepsilon_{\chi x}+(\sin \chi \sin 2 \omega) \varepsilon_{x y}+(\cos \chi \sin 2 \omega) \varepsilon_{x z} \\
& +\left(\cos ^{2} \omega \sin ^{2} \chi\right) \varepsilon_{y y}+\left(\cos ^{2} \omega \sin 2 \chi\right) \varepsilon_{y z}+\left(\cos ^{2} \omega \cos ^{2} \chi\right) \varepsilon_{z z}
\end{aligned}
$$

Knowing both sides of the equation for various $\chi$ and $\omega$, the strain matrix can be determined. Rather than solving an absurdly large system of equations, instead the method of least squares can be applied modeling this system as the sum of six independent variables, each term in parenthesis, with corresponding coefficients, each accompanying strain term. This equation is different than one discussed by [3], which was derived by geometric means. We believe the discrepancy is due to a mathematical error in [3].

## Strain Calculations

Specifically, this least squares routine was run for three $\chi$ rings (110, 200, 211 peaks) for $\chi$ ranging from $-\pi$ to $+\pi$. The fit was performed for fourteen levels of macrostrain, but we will discuss in detail the relative strain case 350. Figure 11a,b, and c plot the the 110, 200, and 211 peaks with the calibrated data in red and the fitted data in blue. Looking at Figure 11c, there is a dip in the data values around $\chi=1.5$. This dip is due to the force apparatus blocking the X -ray from hitting the dector which resulted in a gap in the caked image. The Fourier fitting process adjusts for this. Processing these peaks through the least squares routine mentioned above results in the strain tensor and estimated standard deviations (esds), which are shown in Table 3. Looking at the strain tensor, the axial strain in the $y$ direction corresponds to the direction of the exhibited force and, accordingly, is positve and larger in magnitude than the strain in the other directions. The strains in the orthogonal directions are negative and smaller in magnitude as expected. Figure 12 shows microstrain, in percent strain, versus relative macrostrain, unitless. The shear strains are consistently zero, as mandated by the Fourier fit, thus demonstrating the
validity of this process of finding strain. In addition, the strains in the principle axes increase in magnitude proportionally with marcostrain. However, the strain in the $z$ direction is larger in magnitude than the strain in the x direction. This indicates an anisotropy in the material, either a property of the microstructure or of the strain geometry. Figures 13a-f show show each strain element plotted with their 95\% cofidence intervals. Strain the y and z directions have very small esds indicating a very high level of percision. On the other hand, strain in the x-direction has much larger esds indicating that more data is needed to decrease this noise. To elaborate, the x direction is perpendicular to the sample surface and the displacement in that direction is a function of $\omega,(d \cos \omega)$. While d varies inversely to Q , the relation between Q and $\omega$ is given by: $\omega=\sin ^{-1}\left(\frac{Q \lambda}{4 \pi}\right)$. Even with a large deviation in Q space, say from 41.5 to $42 \mathrm{~nm}^{-1}$ for the 200 peak, cos $\omega$ changes from 0.9469 to 0.9455 ( $-0.13 \%$ ). Thus, strain in the x direction is being defered from effectively only three points, one from each $\chi$ ring, while the strain in the $y$ and z directions is obtained from a much larger population.

## Hydrostatic Strain

Recall the fitting format $Q_{f i t}(\chi)=a_{0}+a_{1} \cos f \chi+b_{1} \sin f \chi$. The $a_{0}$ term refers to a position in Q that can be considered the position of the peak in the caked image. Some $d_{\text {strain }}$ can be determined for every $a_{0}$, (a value in q space), at every level of stain and ultimately translated into hydrostatic strain along the Q vector. Hydrostatic strain refers to axial strain uniform in all directions. Figure 14, shows hydrostatic strain plotted relative to macro-strain for each $\chi$ ring. Notice the hydrostatic strain of 200 peak increases at a much faster rate than the other peaks. This is may be an indication of needing to recalibrate the diffraction image in Fit2D for every strain level. Otherwise, strain is dependent on $h k l$, the peak number. In other words, it
reconfirms the presence of anisotropy in the material which may become more obvious for higher orders of strain.

## CONCLUSION

The strain matrices developed from this method were qualitatively accurate. The microstrains shown in Figure 12 responded to the macro-strains as expected. Furthermore, the strain equations and method of implementation were valid. Further quantitative analysis revealed a directional dependence for strain in the sample. This was found both in the difference between strain in the x and z direction as well as the $h k l$ dependence in the hydrostatic strain. Looking at the Fourier fit, the deviation between the original data and the fitted data appears to increase with strain, shown in Figure 15. However, this deviation, although small, is not symmetric about $\chi$. The Fourier fit used only has a single sine and cosine which fits the data to be symmetric with respect to $\chi$, which is fine for a uniaxial case such as in this paper. However, if a shear strain was introduced that would result in an unsymmetrical arch. Thus, either the mechanism used to exert a force on the nitinol sample was not ideal in introducing a pure axially axial force. The Fourier Fit needs to be more complex in order to fit data with shear strain. In addition, future research can: determine how much information from the diffraction image is needed to extract the strain tensor, experiment with other types of loads, and look at higher levels of strain in relation to the other micromechanical properties. In order to increase the precision of the results, future research should run a new calibration for each level of strain and extract more $\chi$ rings per diffraction image as this paper only deals with three of an available five.

## ACKNOWLEDGEMENTS

This research was conducted at the Stanford Synchrotron Laboratory at the Stanford Linear Accelerator Center. I provide my greatest appreciation to my mentor Apurva Mehta and fellow SULI student Erich Owens. Through them both I have learned multitudes. I thank David Bronfenbrenner for providing me with data. I thank SLAC and the Department of Energy, Office of Science. Lastly, thanks to Stephanie Majewski.

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| Peak Number | Location in Q space (unstrained) | $\mathrm{d}_{0}$ |
| ---: | :---: | ---: |
| 110 | $29.48578921444401 \mathrm{~nm}^{-1}$ | $2.130919834461030 \AA$ |
| 200 | $41.73517701432516 \mathrm{~nm}^{-1}$ | $1.505489075803596 \AA$ |
| 211 | $51.09763355587002 \mathrm{~nm}^{-1}$ | $1.229643110636340 \AA$ |

Table 1: Peak number, Location in $Q$ space, and corresponding d spacing for each peak extracted from Nitinol diffraction patterns.

| $a_{0}=$ same as [ $a_{0}$ ] mentioned in text $=29.48578921444401 \mathrm{~nm}^{-1}$ |
| :--- |
| Calibrant $=\left[\right.$ the original data $-a_{0}$ ] or [the unstrained data- $a_{0}$ ] mentioned in text, a vector of |
| positions in Q-space given in $\mathrm{nm}^{-1}$ |
| $\mathrm{~d}_{0}=2.130919834461030 \AA$ |
| $\mathrm{Q}_{\text {strain }}=$ data for the strained case, a vector of positions in Q-space given in $\mathrm{nm}^{-1}$ |
| Intensity $=$ intensity of the peak |
| $\chi=$ angle relating the diffraction pattern to physical space |
| $\mathrm{Q}_{\text {fit }}=$ A vector of calibrated positions in Q-space given in $\mathrm{nm}^{-1}$ |

Table 2: Definitions for the calibrated fit, referred to as Fourier fit.

| $\varepsilon=10^{-3} \times$ | $-2.57540972854$ | -0.00016054550 0.04144773732 <br> 5.39204211648 0.14624420465 <br>  -4.32147865109 |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| esds $=10^{-3} \times$ | ${ }^{3} \times{ }^{0.2316787755}$ |  | 0.0258427 0.0337903 | 810897 | 0.02567 0.01737 0.0341 | 7551645425 |

Table 3: Strain tensor and estimated standard deviations for relative macro-strain level of 350. This strain tensor is given in the sample space coordinate system.


Figure 1: Visualization of Bragg's Law. Incident beam reflects off of atoms by a scattering angle dictated by Bragg's equation.


Figure 2: Bragg's Law in transmission geometry. $Q$ vector denotes the change in momentum of the X-ray beam ( $I_{0}$ ) and points along the $d$ spacing between atoms. Angles $\chi$ and $\omega$ are used to locate $Q$.


Figure 3: A simplified diffraction pattern. The bright circles are $\chi$ rings, where $\chi$ is the angle from the vertical.


Figure 4: An unstrained diffraction pattern with circular $\chi$ rings. Each ring is referenced by its Miller index, some numbers hkl.


Figure 5: Caked images, straightened $\chi$ rings, of Nitinol in the Austenite phase. Each successive image is under a different level of macro-strain. Notice that the $\chi$ ring progressed from a straight line to an arch of greater eccentricity and eventually begins to disappear. In this process the material is deforming elastically and then undergoing a phase transformation.

Figure 6: Caked images, straightened $\chi$ rings, of nitinol in the martensite phase. Each successive image is under a different level of macro-strain. Notice the change in texture, or twining, as indicated by the intensity poles. As strain increases more, the peaks start to widen, an indication of plastic deformation.



Figure 7: The rig for inducing strain in the sample. The thin film, in red, was pulled out by the moveable crosshead [4].

Relative
macro-strain of 350

Relative
macro-strain of 470


## Unstrained 110 Peak

Location in Q space:
$\mathrm{Q}=29.48578921444401 \mathrm{~nm}^{-1}$
Corresponding $\omega$ :
$\omega=0.23045701838923 \mathrm{rad}$
Unstrained $\mathrm{d}_{0}$ :
$\mathrm{d}_{0}=2.130919834461030 \AA$


Figure 9: The process of finding $d_{0}$ for the $\mathbf{1 1 0}$ peak. The original data, top, has some unexpected deviations which are attributed to the caking process. Fitting this data allows for a calibration factor to be extracted, which has been applied to the unstrained case, shown at the bottom.


Figure 10: Sample geometry. Angles $\chi$ and $\omega$ are the same from Figure 2. The force is in the $y$ direction.


Figure 11: The Fourier fit for each peak (110, 200, and 211) at a relative macro-strain of 350


Figure 12: Strain in the direction of load, the cyan line, increases proportionally with the load. Strain in the orthogonal directions is negative and proportional to the load as well. Shear strain is zero for all load levels.


Figure 13.a


Figure 13.b


Figure 13.c


Figure 13.d


Figure 13.e


Figure 13.e


Figure 14: Hydrostatic strain is dependent on hkl.


Figure 15: The Fourier fit used to smooth the data we appropriate for small levels of strain, but had trouble fitting the data for higher strain values.

# Speeding up the Raster Scanning Methods used in the X-Ray Fluorescence Imaging of the 

## Ancient Greek Text of Archimedes

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August 2, 2006

Prepared in partial fulfillment of the requirements of the Office of Science, U.S.
Department of Energy Science Undergraduate Laboratory Internship (SULI) Program under the direction of Dr. Uwe Bergmann at the Stanford Synchrotron Radiation Laboratory division of Stanford Linear Accelerator Center.

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## Table of Contents

Abstract ..... 3
Introduction ..... 4
Materials and Methods .....  6
Results and Discussion ..... 9
Conclusions ..... 10
Acknowledgements ..... 11
References ..... 11
Tables. ..... 12
Diagrams ..... 12
Figures ..... 12


#### Abstract

Speeding up the Raster Scanning Methods used in the X-Ray Fluorescence Imaging of the Ancient Greek Text of Archimedes. MANISHA TURNER (Norfolk Sate University, Norfolk, VA 23504) DR. UWE BERGMANN (Stanford Linear Accelerator Center, Menlow Park, California 94025).


Progress has been made at the Stanford Linear Accelerator Center (SLAC) toward deciphering the remaining 10-20\% of ancient Greek text contained in the Archimedes palimpsest. The text is known to contain valuable works by the mathematician, including the Method of Mechanical Theorems, the Equilibrium of Planes, On Floating Bodies, and several diagrams as well. The only surviving copy of the text was recycled into a prayer book in the Middle Ages. The ink used to write on the goat skin parchment is partly composed of iron, which is visible by x-ray radiation.

To image the palimpsest pages, the parchment is framed and placed in a stage that moves according to the raster method. When an x-ray beam strikes the parchment, the iron in the ink is detected by a germanium detector. The resulting signal is converted to a gray-scale image on the imaging program, Rasplot. It is extremely important that each line of data is perfectly aligned with the line that came before it because the image is scanned in two directions.

The objectives of this experiment were to determine the best parameters for producing well-aligned images and to reduce the scanning time. Imaging half a page of parchment during previous beam time for this project was achieved in thirty hours. Equations were produced to evaluate count time, shutter time, and the number of pixels in
this experiment. On Beamline 6-2 at the Stanford Synchrotron Radiation Laboratory (SSRL), actual scanning time was reduced by one fourth. The remaining pages were successfully imaged and sent to ancient Greek experts for translation.

## INTRODUCTION

Throughout history, science and religion have been at odds over the right to explain how and why things happen. While both sides have innovated since medieval times, it would seem that yet another battle inadvertently began during exactly that dark period...

Centuries ago, ancient Greek mathematical mastermind Archimedes documented his ideas, many of which were far advanced for his time. In 4 A.D., as there were no printing presses to copy an author's work, scribes painstakingly copied Archimedes' works by hand onto parchment made of goatskin. During a series of wars in the Middle Ages when paper was a scarce commodity, a Christian monk in need of a prayer book recycled a copy of Archimedes' work. This was accomplished by erasing the genius's writing with a weak acid (like lemon juice) and scraping it with pumice stone [1]. The parchment was then folded parallel and bound such that Archimedes' text lay perpendicular to the monk's prayers [2]. This now makes the work a palimpsest, a writing material (as a parchment or tablet) used one or more times after earlier writing has been erased.

These invaluable copies of Archimedes' work contain the details of many of his ideas, such as floating bodies and the equilibrium of planes, and the treatise Method of Mechanical Theorems [1]. First discovered in 1906 and resurfacing again in the 1990’s,
the palimpsest has gone through experiments to safely and effectively read what lies beneath the soot from centuries of extreme damage from mold, forgery, candle wax, and ink. A great deal of the text has been read by visible or ultraviolet light during six years of careful analysis and restoration through a method called multi-spectral imaging [3]. In this process, light of various wavelengths is used to differentiate between the two manuscripts [2]. Unfortunately, multi-spectral imaging proved ineffective in reading of text (about 10-20\%) because of obstructions like forgery paintings, dirt, mold, glue or other parchment.

At the Stanford Synchrotron Radiation Laboratory (SSRL), a kind of radiation known as synchrotron light is produced when electrons, racing at nearly the speed of light, move around a curved storage ring, emitting radiation ranging from x-ray to infrared wavelengths in the process [4]. It was realized that, because the parchments were written on with ink containing iron, x-ray fluorescence could be used to see Archimedes' work beneath the damage. X-ray fluorescence occurs when a photon strikes an atom (such as iron) and is either absorbed or scattered. If the ray is absorbed, the photoelectric effect takes place [2], in which photons of significant energy knock electrons from the inner shells out, leaving electron holes. These holes launch the atom into a highly energized state. Electrons from outer shells swiftly fill the available spaces to return the atom to its ground (lowest energy) state. This rapid movement of electrons gives off photons characteristic of the atom. Because each element has a unique set of energy levels that produce energy-specific x-rays, it is possible to obtain the elemental composition of a sample.

The integral component of this experiment is fine-tuning the scanning methods used in the project. The speed with which the work is deciphered is increased by synchronizing the scanning speed and read-out time. Originally, the time it took for a $40 \mu \mathrm{~m}$ beam to decipher half a page (approx. 8,312,500 pixels) was thirty hours with a resolution of 600dpi. The pages were scanned using the raster format, which is continuous in both the positive and negative $x$-directions, then stepwise down in the $y$ direction (See Fig. 1). However, it would be advantageous to scan the page faster.

The purpose of this project is to test and commission a new readout system that was built in order to minimize the dead time and speed up the readout time, allowing for faster scans without loss of resolution.

The main constraints being adjusted are motor speed, count time and shutter time, which directly affect how well subsequent scanning lines are adjusted and how well the edges of the images are lined up. Accomplishing this will allow the researchers to use the improved faster scanning method.

## MATERIALS AND METHODS

In order to speed up the raster scanning method, a new readout system developed at SSRL was commissioned. The high-intensity $x$-ray beam from the original experiment was replaced with a Class II He Ne laser, and a photodiode detector was substituted for the original germanium detector. A template made from a thick paper material (used in manila folders) was scanned for image testing. This material was more practical than cardboard or traditional writing paper because its thickness is closer to the goat skin used in the original text.

The template was attached to a frame that slid directly into a stage positioned between the laser and detector. The photodiode detector was placed across from the laser beam to measure the beam's transmission through the template. Scanning with this material produced clear images; however, the edges of the cutout lines were not completely straight. Scanning perfect vertical lines is very important because, since the line scanning is in both directions (see Diagram 1), if the interval between read-out time and scanning speed isn't perfect, the lines of the image do not line up. Therefore, knife edges were scanned to produce perfectly aligned images. Later, printed text on transparency was used to produce nice images of complete text. The stage was driven by two motors, allowing x -range data to be recorded when scanning in both directions.

All data were recorded "on the fly," or while the scanning was underway. As soon as the beam reached a cutout, the photodiode detector collected the transmission. For each beam, the detector would send a current to an amplifier where was converted to a voltage. The voltage signal was changed to a frequency via a voltage/ frequency converter, resulting in a number of counts. The grey-scaling program, Rasplot, then produced an image based on the numerical values. The count time, the time it took the template to move between readouts, was tested for several different scanning distances. To calculate the count time for each distance, it was necessary to first calculate how many pixels were contained in that distance. This was done by dividing the scanning distance by the pixel size (40microns [ $\sim 600 \mathrm{dpi}]$ ),

$$
\begin{equation*}
\text { *40 } \mu \mathrm{m}=0.04 \mathrm{~mm} \rightarrow[\text { Distance }(\mathrm{mm})] /[0.04 \mathrm{~mm}]=\text { no. pixels. } \tag{1}
\end{equation*}
$$

Next, a fixed motor speed of 2160steps/sec and rate of 157.48 steps/millimeter were used to calculate how many pixels were scanned per second,
[2160steps/sec]*[1mm/157.48steps]*[no. pixels/distance (mm)]= pixels/sec
Finally, because count time is reported in seconds/ pixel, it was easily found as the inverse of equation two,

1/[pixels/second]= count time (sec/ pixel)
The shutter box is a device used to safe-guard the parchment against radiation damage from the x-ray beam while the endpoints are exposed. The shutter opened at the start of each line scan and closed at the end of each line scan, where the stage would move to the next line. The amount of time the shutter took to open greatly affected the image's alignment and was adjusted, for each distance, according to the following formula,

$$
\begin{equation*}
\text { [Pixels] } \times \text { [count time (sec/ pixel)]= shutter time (sec) } \tag{4}
\end{equation*}
$$

The most important part of this experiment was determining the best count time and shutter time for each scanning distance. These values are ideal when the pixels of the resulting image at the end of each scan line up perfectly. Tests were run to determine the best values for count time and shutter time for $60,70,80,160,170$, and 200 mm scanning distances (See Table 1). By commanding the Rasplot program to plot each image on a single pixel scale, any offset in time could be seen almost immediately, after about three line scans. Count time proved most difficult to adjust, as an offset of even a microsecond would cause the pixels to be misaligned and distort the image immensely. Correctly determining shutter time was vital because it ensured that a) the edges of the image were straight and more importantly b) that the parchment would not be exposed to x-rays when the motor movement stopped at the end of each line. If the count time was significantly off, aspects of the image such as sharp edges and curves were harder to determine and
would appear blurry or stretched (see Images 1 and 2). These times, remarkably, were perfected to microsecond precision.

A series of long scans were commissioned to determine how well the program could perform, producing well-aligned images at the desired count time for each distance. An 80 mm scan of the template was run overnight, at a count time of 0.003001 seconds per pixel and a shutter time of 5.8 seconds. The resulting image was satisfactory because the characters were easy to make out, which means the count time was excellent; however, it was difficult to tell whether the shutter time was best because the cutouts were made by hand with a razor and did not image straight vertical lines (see Image 2). In order to test for shutter time, knife edges were scanned overnight to produce an image of a full 80 mm scan. The image did not align completely and needed to be corrected. The shutter time was adjusted slightly to 5.785 seconds, producing the best image (see Image 3). After the best scanning conditions were optimized, the stencil was scanned again and produced a perfectly aligned image (see Image 4). A long scan of text on transparency was imaged to produce a full-text image (see Image 5).

The motors also needed to be considered, as they had to be monitored to prevent over heating. A thermocouple was attached to the stepper motor and a fan was placed close by to make sure the motor temperature did not exceed 70 degrees celsius.

## RESULTS AND DISCUSSION

It was determined that the very best images resulted from very carefully adjusted count times and the corresponding shutter times. The count time proved most important in producing perfectly aligned images, as an offset of merely a microsecond would
introduce visible distortions in the image from misalignment of subsequent lines. The shutter time, however could be manipulated according to the desired count time without having to be as meticulously perfect.

The new parameters found in this experiment have sped up the Raster scanning method by $\sim 5$ times the speed accomplished in previous experiments (a remarkable 12hours/ page). The helpfulness of this experiment in accomplishing better images in less time is evident in the scanning of the ancient texts of Archimedes conducted at Beamline 6-2 at SSRL this summer. The team from SSRL, the Walters Art Museum in Baltimore and the other collaborating institutes set up the experiment according to the newly found parameters. The final scans were completed on Monday, August 7, 2006. One of the significant new findings was the complete image of a previously only partly seen diagram in Archimedes’ most important work 'The Method of Mechanical Theorems’. It was published in Science on August 11, 2006 [5].

## CONCLUSIONS

The palimpsest was successfully imaged using the new readout system achieved from this experiment. The resulting images were sent to ancient Greek experts for translation and made available online at www.archimedespalimpsest.org. The total time taken to image one page of parchment was reduced to 12 hours, an improvement by a factor of 5 from the original time of approximately 30 hours. Future experimentation with the palimpsest may involve alternative imaging methods such as confocal imaging and scanning for other atoms (like calcium) to make the text more legible for the ancient Greek experts.

## ACKNOWLEDGEMENTS

I would like to thank my mentor, Dr. Uwe Bergmann, for giving me the opportunity to work on such an amazing project and helping me to gain better understanding of all that goes into conducting quality research. I greatly admire you for the work you have done and I am so grateful I had the chance to work with you. I would also like to thank Martin George for supporting me and helping to make sure things were running properly. Thank you so much to the staff at SSRL who offered technical support on many occasions. Finally, thank you to the Department of Energy for providing me a chance to participate in the SULI program, which was an experience I will never forget.

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## Tables

| Scan Distance <br> $(\mathbf{m m})$ | x-Num Pts. (pixels) | Count Time <br> (secs/pixel) | Shutter Time <br> (secs) |
| :---: | :---: | :---: | :---: |
| 60 | 1500 | 0.003027 | 4.33 |
| 70 | 1750 | 0.003012 | 5.065 |
| 80 | 2000 | 0.003001 | 5.785 |
| 160 | 4000 | 0.0029605 | 11.64 |
| 170 | 4250 | 0.0029585 | 12.37 |
| 200 | 5000 | 0.002953 | 14.55 |

Table 1: Count time, shutter time and number of pixels determined for various scanning distances.

## Diagrams



Diagram 1: The Raster scanning format.

Figures


Figure 1: The class II He Ne laser was positioned in front of the stage (below).


Figure 2: The stage, positioned between the laser and detector, held the parchment in its frame for scanning.


Figure 3: The photodiode detector, positioned behind the shutter box.


Figure 4: The shutter box, positioned behind the stage, used air pressure (green tubing) to open and close shutters.


Figure 5: The experimental setup, showing knife edges mounted on stage for scanning (x-motor not shown).

## Images

# Grchtmedes 

Image 1: Part of 80 mm scan of transparency. Image is stretched because of offset in count time.


Image 2: 80 mm scan of template is blurry and stretched because of offsets in count time and shutter time.
 a shutter time offset of only one pixel (see Table 1).


Image 4: 80mm scan of stencil, repeated using new parameters from knife edge scan (see Table 1).


Figure 5: perfectly aligned 80mm full-text scan of
transparency, scanned with new parameters (see Table 1).

# Comparison of Non-Redundant Array and Double Pinhole Coherence Measurements with Soft X-rays 

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August 25, 2006

Prepared in partial fulfillment of the requirements of the Office of Science, U.S.
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## Table of Contents

Abstract ..... 3
Introduction ..... 4
Methods and Materials ..... 5
Results ..... 8
Discussion ..... 10
Acknowledgements ..... 12
References ..... 12


#### Abstract

Comparison of Non-Redundant Array and Double Pinhole Coherence Measurements with Soft X-rays, GABRIEL WEIL (Northwestern University, Evanston, IL 60201) WILLIAM SCHLOTTER and JAN LÜNING (Stanford Synchrotron Radiation Laboratory, Menlo Park, CA, 94025)

Experiments on the future Linac Coherent Light Source (LCLS) and other Free Electron Lasers will need to be performed on a single-shot basis. The double pinhole method of measuring spatial coherence requires a separate measurement, with a different pinhole separation distance, for each length scale sampled. This limits its utility for LCLS. A potential alternative uses a Non-Redundant Array (NRA) of apertures designed to probe the coherence over the range of length scales defined by their physical extent, in a single measurement. This approach was tested by comparing diffraction patterns from soft xrays incident on double pinhole and NRA absorption mask structures. The double pinhole fringe visibility data serve as discrete reference points that verify the continuous spectrum of the NRA coherence data. The results present a quantitative analysis of the double pinhole coherence measurements and a qualitative comparison to the NRA images.


## Introduction

In order to take advantage of the over ten orders of magnitude increase in peak brilliance anticipated from the LCLS (Linac Coherent Light Source), experiments will need to be designed to operate on a single-shot basis. Such designs must accommodate for shot to shot variations in the source parameters. Since these parameters influence the spatial coherence, it will be important to have a means of measuring spatial coherence on many length scales simultaneously.

The standard method of measuring spatial coherence is to determine the visibility of interference fringes that result from diffraction patterns of radiation incident on double pinhole masks of varying pinhole separations. As seen in Eq. (1), this fringe visibility, V, is directly proportional to the mutual coherence function, $\gamma(\tau)$, with a proportionality constant that depends on the uniformity of the intensities, $\mathrm{I}_{1}$ and $\mathrm{I}_{2}$, incident on the two pinholes [1].


Figure 1: Simplified beam view.

Eq. (1)

$$
V=\frac{2 \sqrt{I_{1}} \sqrt{I_{2}}}{I_{1}+I_{2}}\left|\tilde{\gamma}_{12}(\tau)\right|
$$

This method, of course, requires a source whose coherence properties remain stable long enough for several separate measurements. An alternative to this approach uses a Non-Redundant Array (NRA) of apertures arranged to include all possible
separation distances, thus enabling simultaneous measurements of the spatial coherence of many length scales.

Coherent scattering patterns from the NRA produce images that represent the convolution, see Eq. (2), of the ideal diffraction pattern, $I$, from the set of apertures with the Fourier transform of the mutual coherence function, $C$. Deconvolution can be used to extract the unknown mutual coherence function from the known ideal diffraction pattern [2].

Eq. (2)

$$
\left(I^{*} C\right)(x)=\int I(u) C(x+u) d u
$$

A similar arrangement, known as the Uniformly Redundant Array (URA), was originally developed for use in astronomical imaging [3] and has been applied to soft xray spatial coherence measurements at the Lawrence Livermore National Laboratory laser source [4]. Double pinhole coherence measurement experiments have also been performed on extreme ultraviolet and soft x-ray undulator radiation at the Advanced Light Source [5].

Though today's advanced x-ray sources can be tuned to a certain photon energy, the radiation produced always has finite bandwidth. The energy of greatest photon flux is referred to as the undulator peak, while the point on the higher energy side of the peak where the intensity is about $50 \%$ of its value at the peak is referred to as the blue edge. The blue edge is typically used in coherence experiments because the photons at that energy have taken the straightest path and thus exhibit the lowest degree of divergence.

In this experiment, discrete data points from double-pinhole experiments were used to verify the accuracy of the continuous coherence function provided by the NRA analysis.

## Methods and Materials

The coherence properties of soft x-ray synchrotron radiation were studied by observing the visibility of interference fringes produced by diffraction at the apertures of double pinhole and NRA masks. Absorption films were prepared by depositing a 900 nm


Figure 2: Scanning Electron Microscope (SEM) image of NRA Au mask with aperture separation distances from 0.5 to $12 \mu \mathrm{~m}$ and 900 nm thickness
thick layer of Au onto a 100 nm thick $\mathrm{Si}_{3} \mathrm{~N}_{4}$ membrane at a rate of $0.6 \mathrm{~nm} / \mathrm{s}$. In order to achieve the requisite aspect ratio, a Focused Ion Beam (FIB) was used to mill double pinhole masks, see Figs. 3 and 4, with center to center distances of 1, 3, 5 and $7 \mu \mathrm{~m}$ and pinhole diameters ranging from 100 to 300 nm . The NRA absorption masks were also fabricated using a FIB, see Fig 2.


Figure 3: SEM image of double pinhole mask with $1 \mu \mathrm{~m}$ separation


Figure 4: SEM image of double pinhole mask with $7 \mu \mathrm{~m}$ separation

To set the groundwork for similar studies on LCLS, the experiment was performed on the undulator at beamline 5-2 at SSRL, at 420 eV .

As in Fig. 5, the divergence of the beam was controlled by manipulating a set of movable horizontal slits. Images were acquired at four horizontal aperture settings identified by their relative intensity incident on the sample, at $100 \%, 12.7 \%, 5 \%$ and $2.4 \%$ relative intensity. The intensity loss results from constraining the aperture so that the effective source size was reduced, which has the effect of increasing spatial coherence. In all cases, the beam was then focused with a series of spherical mirrors and the energy was selected with a spherical grating monochromator. The resulting radiation was coherently scattered by the double pinhole and NRA samples to form a diffraction pattern on the detector. The CCD camera uses a backside illumination chip for maximum quantum efficiency [6] and uses thermoelectric cooling in order to minimize dark noise The CCD is composed of a $1340 \times 1300$ array of $20 \mu \mathrm{~m}$ pitch pixels and the distance between the sample and the detector is 30 cm .


All the aforementioned measurements were made on the blue edge. An additional data set, however, was acquired on the undulator peak for the $12.7 \%$ relative intensity setting.

Double pinhole fringe visibilities were determined by taking horizontal line cuts from 2-dimensional images and sampling maximum-minimum pairs from each line cut to apply the visibility formula:

Eq. 3

$$
V=\frac{I_{\max }-I_{\min }}{I_{\max }+I_{\min }}
$$

where $\mathrm{I}_{\max }$ and $\mathrm{I}_{\text {min }}$ are corresponding relative maxima and minima on the intensity curve, as shown in Fig. 6.


## Results

The double pinhole data suggest that there is an upper limit on the spatial coherence of the undulator at beamline 5-2 at SSRL at certain length scales. At $2.9 \mu \mathrm{~m}$, there is no significant variation between the $12.7 \%, 5.0 \%$ and $2.4 \%$ relative intensity, suggesting that the aperture setting only begins to influence coherence after a certain threshold value that depends on the length scale. This view is supported by the fact the $12.7 \%$ relative intensity curve begins to deviate from the two smaller aperture data sets by the third point at $4.9 \mu \mathrm{~m}$ and pulls away completely by the fourth point at $6.8 \mu \mathrm{~m}$. The
$100 \%$ relative intensity curve appears to reach this threshold by the first data point at 1.0 $\mu \mathrm{m}$, as it already shows significantly lower visibility there and the deviation increases steadily with increasing length scale. We might therefore expect the $2.4 \%$ and $5.0 \%$ relative intensity curves to diverge on length scales greater than those investigated in this experiment.

Visibility vs. Pinhole Separation for Four Source Aperture Settings
(Percentage of Maximum Intensity)


The data from the undulator peak, compared with the blue edge, indicate that there is a uniform drop in coherence across length scales. This may be because isolating the undulator peak as opposed to blue edge selects for photons that have greater intrinsic divergence that is not related to any particular region in space. In contrast, effective source size, which determines relative intensity, is a spatial parameter and thus can be expected to have a dependence on the length scale sampled by the double pinhole mask.

Visibility vs. Pinhole Separation at Undulator Peak and Blue Edge


Figure 11
Pinhole Separation ( $\mu \mathrm{m}$ )
The NRA data indicate a general trend that coherence decreases with increasing relative intensity. Since the quantitative analysis is ongoing, we cannot draw any conclusion regarding whether the threshold effects that appear with separation distance and relative intensity are detectable in the NRA images. Analysis of this data is ongoing.


Figure 12: Raw NRA Image at 100\% Relative Intensity


Figure 13: Raw NRA Image at 12.7\% Relative Intensity


Figure 14: Raw NRA Image at 5.0\% Relative Intensity

## Discussion

The limited spatial resolution of the CCD had the effect of producing systematically lowered visibility measurements, because minima values are raised and maxima values are lowered by offset extrema. This error is more pronounced for larger
pinhole separation distances where the fringes are more tightly spaced. The statistical error was at acceptable levels and can largely be accounted for by the necessity of maxima and minima coming from different points on the envelope. To cancel out these effects, the intervals were always defined such that the maximum was to the left of the minimum and an equal number of intervals were taken from each side of the central maximum. There was no significant variation in visibility between line cuts for a given image.

The double pinhole data indicate that it will probably not be feasible to produce a control NRA image that represents the ideal diffraction pattern, due to the apparent coherence limit on certain length scales. However, this ideal type is theoretically derivable and should prove useful with higher quality images at various coherence settings.

In order to explore the full range of the NRA and investigate the threshold behavior relating length scale and source size, it would be interesting to use pinholes of greater separation distances. This, however, would exacerbate the resolution problems faced in this experiment and would likely require longer wavelength radiation or increasing the distance between the sample and the CCD to acquire reliable data. Moving to lower photon energy would increase the risk of encountering higher harmonics that would distort the data and moving the detector back would require restructuring of the experimental station, so modifications are required to fully explore this phenomenon.

The NRA method holds promise for application on LCLS and high peak brilliance sources, but further testing is required. The trends visible in the NRA images are encouraging and merit exploration. Advances in this area will allow more effective use of LCLS and other Free Electron Lasers to study coherence on ultra-fast time scales.

## Acknowledgements

The author would like to thank U.S. Department of Energy, Office of Science for providing me with the opportunity to participate in the SULI program. I would also like to thank my mentors, William Schlotter and Jan Lüning, as well as Ramon Rick and all the other members of the group that supported me. Portions of this research were carried out at the Stanford Synchrotron Radiation Laboratory, a national user facility operated by Stanford University on behalf of the United States Department of Energy, Office of Basic Energy Science.

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[^0]:    ${ }^{1}$ An elliptical galaxy is an ellipsoid, or a three-dimensional ellipse, as shown in Figure 5. Viewed from Earth, it appears as an ellipse in the sky.
    ${ }^{2}$ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[^1]:    ${ }^{3}$ The magnitude scale is a logarithmic scale that describes the relative brightness of stars, with the star Vega ( $\alpha$ Lyrae) defined as having magnitude 0.
    ${ }^{4}$ STS-DAS is a product of the Space Telescope Science Institute, which is operated by theAssociation of Universities for Research in Astronomy, Inc. for the National Aeronautics and Space Administration.
    ${ }^{5}$ Ellipticity is defined as $f=1-a / b$, where $a$ is the semi-major axis of the ellipse, and $b$ is the semi-minor axis of the ellipse. An ellipse with $f=0$ is a circle.

[^2]:    ${ }^{6}$ VLA data courtesy of the National Radio Astronomy Observatory/Associated Universities, Inc.

