RECORDING SYSTEM MODELING FOR HEAT ASSISTED MAGNETIC RECORDING

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Scope and Objectives

In this proposed study, we plan to utilize a comprehensive recording model developed for heat assisted magnetic recording (HAMR) to identify all the necessary requirements for medium microstructure and magnetic properties, near field heating profile, and magnetic head field for achieving targeted area densities. Resulting recording SNR and track edge characteristics will be the criteria for evaluating area density capability. The objectives of this study include (1) obtaining critically needed understanding of HAMR recording physics; (2) comprehending the requirements of the medium magnetic properties, especially properties at recording temperatures for achieving area density target; (3) understanding thermal conductivity requirement for HAMR medium, both lateral and vertical, for achieving target recording performance; (4) optimizing overall system design to achieve target area density capability for HAMR technology; and (5) providing the understanding of recording and noise characteristics.

Recording System Modeling Capability

Combining thermal modeling and dynamic micromagnetic modeling, we have built a very comprehensive recording system model for simulating actual heat assisted recording process at a wide range of conditions. The model combines thermal modeling and micromagnetic modeling to simulate dynamic recording processes with heating of the medium via near field transducer.

In this section of the proposal, we give a brief review of the model and its current capabilities.

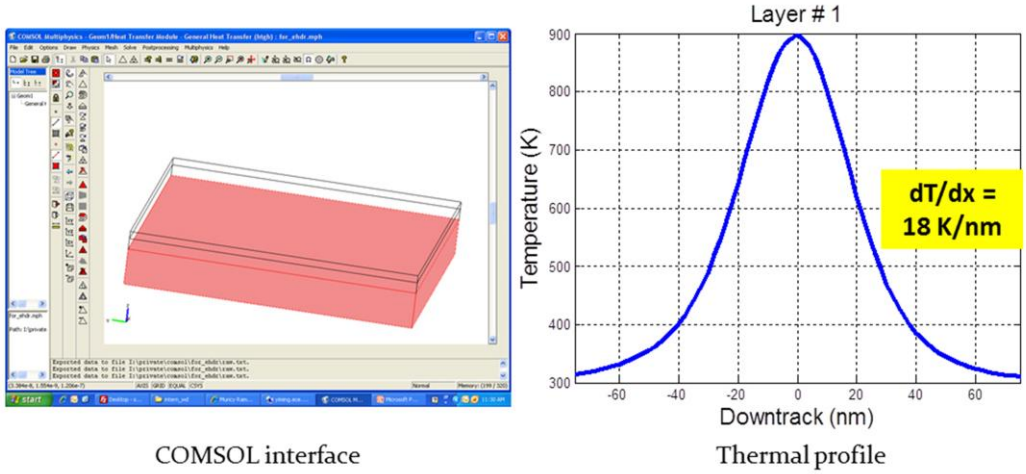

Fig. 1. *Left*: A layered thin film medium modeled in COMSOL. *Right*: Calculated thermal profile of a near field heating spot in a medium.

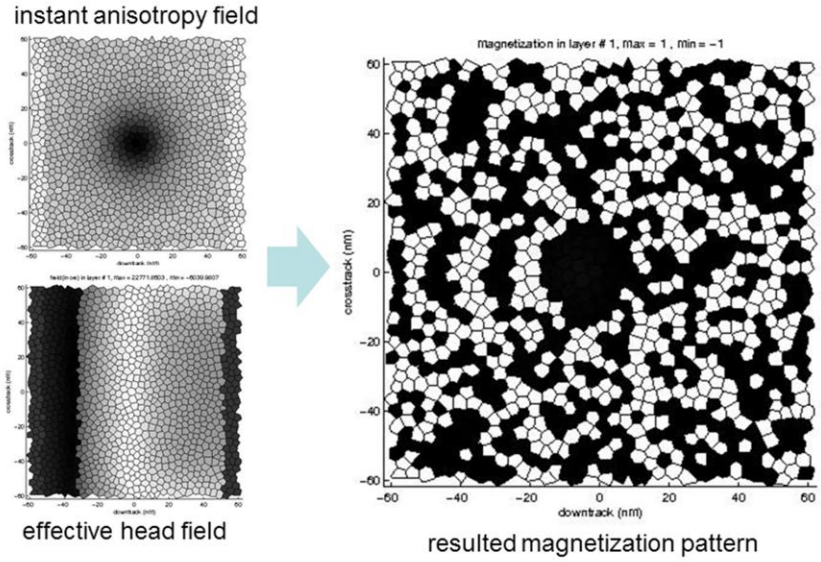

Fig. 2. *Upper-left*: An instant snap shot of calculated anisotropy field in the vicinity of the heating spot.

Lower-left: Calculated effective magnetic head field.

Right: Simulated recorded bit patterns in an ac erased background.

Figure 1 shows the calculated thermal profile in a recording medium. The thermal profile is calculated using COMSOL software with inputs of medium thermal conductivities of multiple layers in a thin film medium. With the obtained thermal profile, anisotropy field distribution of the grains in the medium can be calculated according to either measured or modeled temperature dependence of the anisotropy field. Using calculated recording head field and take into consideration of disk motion during recording, recording process can be simulated using the Landau-Lifshitz-Gilbert equations, as shown in Fig. 2.

Apart from temperature dependence of intrinsic magnetic material parameters, such as magnetization and anisotropy, we also added thermal magnetic excitation of the mean

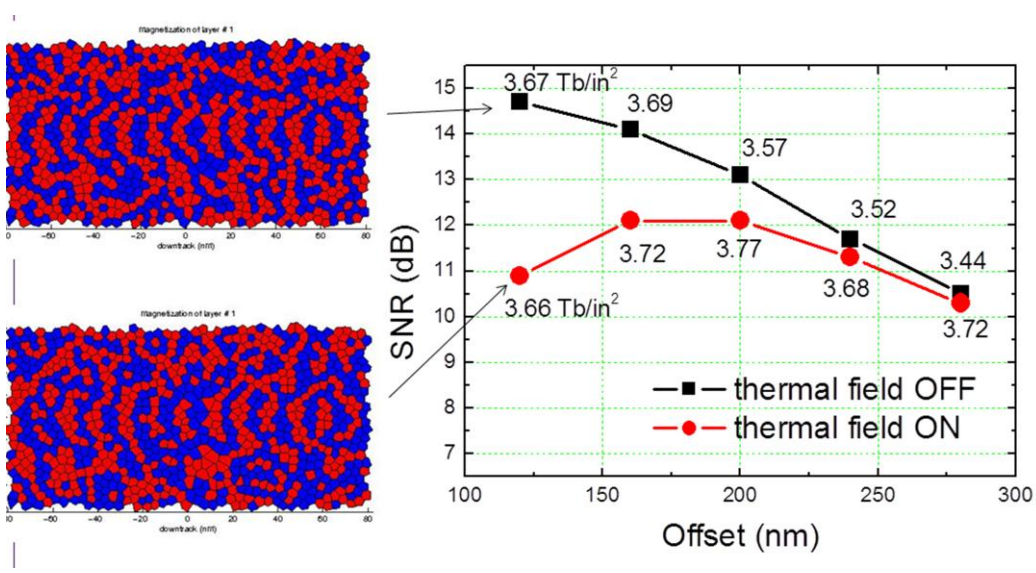

Fig. 3. Calculated medium SNR at various area densities, indicated by the number beside a symbol, with thermal excitation added (red) and without (black). The pictures on the left are two recorded patterns for the two cases indicated. The horizontal axis indicates the position of the heating spot relative within the recording head gap (large ring head).

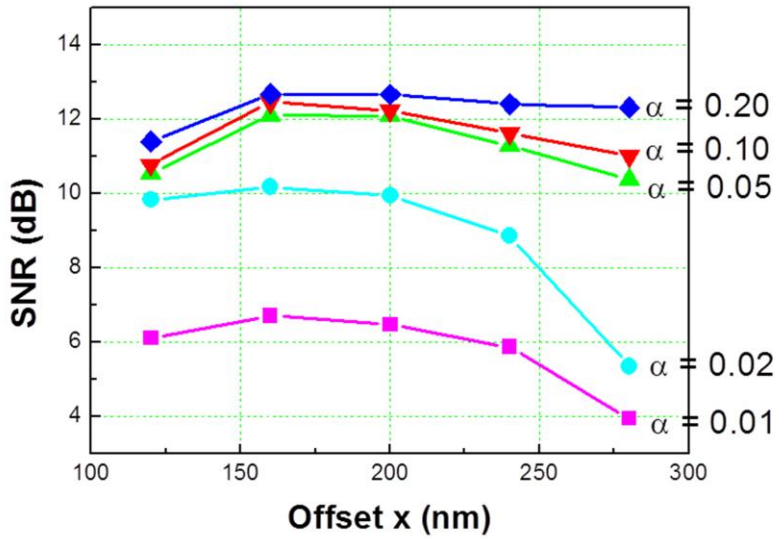

Fig.4. Calculated medium recording SNR near 4Tbits/in^2 area density as a function of relative position of the heating spot within the used ring head gap (gap-width 1000nm with center at offset=500nm). SNR are plotted for various values of medium Gilbert damping constant α. As the results shown, a relatively large α is important.

Magnetization orientation by adding random effective fields, the same way that thermal mag-noise is modeled in a read head free layer. This effect can be very significant at certain conditions and can give rise to significant difference in SNR of the obtained transitions in simulated recording processes. Figure 3 shows the calculated recording SNR as a function of heating spot position relative to trailing edge of a ring head gap of a gap length 1000nm wide. When the field angle is not at optimal, the effect of thermal magnetic excitation on the magnetization orientation during recording processes is significant.

Figure 4 shows calculated medium recording SNR as a function of the heating spot position relative to head write gap for various values of the medium Gilbert damping constant. The damping constant needs to be sufficiently high for optimizing recording performance. At the optimal write field angle determined by the optimal position of the heating spot, the required damping constant is significantly relaxed when the recording field angle is at the optimum value.

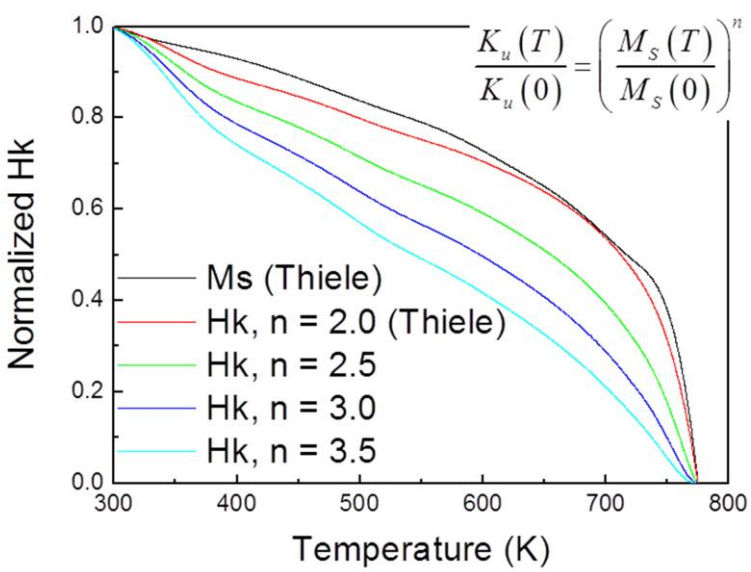

Fig.5. Different temperature dependences of medium anisotropy field used for calculating the resulting recording performance. The greater the power index n in the inset equation, the lower the temperature gradient of the anisotropy.

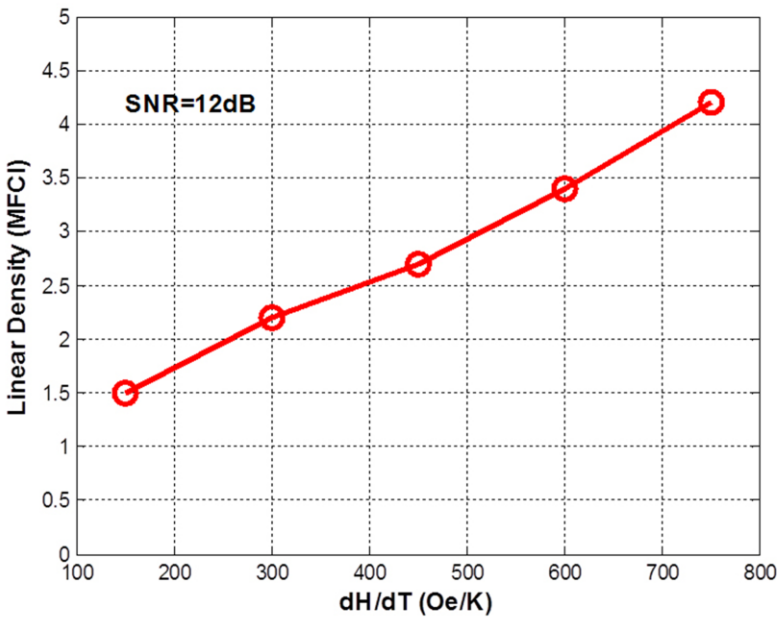

Fig.6. Calculated linear density capability requiring a SNR=12dB as a function of temperature gradient of anisotropy field. Lower temperature gradient of the anisotropy field will result in a lower linear density capability due to resulted higher transition jitter.

The model also enables direct evaluation of the impact by essentially any medium magnetic properties on the medium recording SNR and the resulting area density capability. Figures 5 and 6 show an example on evaluating the impact of the temperature gradient of medium anisotropy field at the recording temperature. With using the temperature dependences shown in Fig. 5, we simulated recording of over 200 bits at various linear densities at the same track width. At a given linear density, a lower the temperature gradient of the anisotropy field yield a much degraded recording SNR due to enhanced transition jitter noise. If we insists an SNR=12dB requirement, this translates into a linear density capability limitation as shown in Fig. 6. A low temperature gradient of the anisotropy field will yield a lower linear density.

In summary, the developed system recording model for HAMR process is quite comprehensive and capable. In this proposed research, we plan to further build and refine the model so that it can be more accurately describe the actual HAMR processes and more importantly to use it to understand the actual HAMR processes.

Technical Research Plan

We will perform combined thermal and micromagnetic modeling to provide guidelines to system design for heat assisted magnetic recording, or HAMR, at targeted area density.

1. Understanding the underlying physics during recording process

Actual physics of the magnetization behavior near the Curie temperature remains to be unclear. Since the coherence of the spins within a medium grain is greatly compromised by the thermal excitation, the Landau-Lifshitz-Gilbert equation may no longer be adequate to describe the magnetization vector within a magnetic grain for a given effective field. Bloch equation has been quite successful in describing a collection of spins in biomaterial which

has led to a tremendous success in nuclear magnetic resonance imaging (MRI). Although there lacks of satisfactory justification on the validity of applying Bloch equation on a collection of spins with ferromagnetic exchange coupling and thermal excitation of comparable strength, a thorough and systematic study is of critical importance to be able to correctly model the recording process.

We plan to perform recording simulation using the combined Landau-Lifshitz-Bloch equation for solving magnetization near Curie temperature instead of just the Landau-Lifshitz-Gilbert equation. Comparison of resulted recording performance between the uses of the two equations will be made to identify characteristic difference in the obtained recorded bit patterns. The following gives the combined LLB equation.

$$\begin{cases} \dfrac{dM_x}{dt} = -\gamma\left(\vec{M}\times\vec{H}\right)_x - \dfrac{\lambda}{M_s}\left(\vec{M}\times\vec{M}\times\vec{H}\right)_x - \dfrac{M_x}{T_2} \\ \dfrac{dM_y}{dt} = -\gamma\left(\vec{M}\times\vec{H}\right)_y - \dfrac{\lambda}{M_s}\left(\vec{M}\times\vec{M}\times\vec{H}\right)_y - \dfrac{M_y}{T_2} \\ \dfrac{dM_z}{dt} = -\gamma\left(\vec{M}\times\vec{H}\right)_z - \dfrac{\lambda}{M_s}\left(\vec{M}\times\vec{M}\times\vec{H}\right)_z - \dfrac{M_z - M_0}{T_1} \end{cases}$$

Without the Bloch relaxation terms, the Landau-Lifshitz part conserves the amplitude of the magnetization. The Bloch relaxation terms yield the change of magnetization amplitude during a reversal along the switching direction at a given temperature. We expect the parameter T_1 and T_2 are strong function of temperature near the Curie point and understanding their temperature dependence is an important part of this proposed study.

Experimental validation of the use of either equation will be an important part of this study. We plan to perform direct comparative study with experimental results, which can be obtained through collaboration with engineers at some of the ASTC or DSSC sponsoring companies.

We know for a fact that the Landau-Lifshitz-Gilbert equation is mostly correct in describe magnetization away from Curie temperature for transition metal materials. It is conceivable that some combined description of the LLG equation and the Bloch equation would end to be the most optimal description of the magnetization near the Curie temperature. Comparative analysis between modeling and experimental results should be able to quantitatively determine if the combined description is necessary.

It is our understanding there will be a project on HAMR magnetization switching physics near Curie temperature. We plan to learn from then on any improved understanding and incorporate into this system modeling tool if appropriate. Definitely, it is our intention to build close collaboration with these project teams so that we have necessary understanding on how to incorporate their findings to refine our model.

2. Investigation of pulse laser heating schemes

We plan to study the recording performance characteristics of using pulsed laser heating in contrast to the CW operation. Although this scheme is mainly designed for the reliability of near field transducer, the corresponding impact to the actual recording performance needs to be understood. This modeling requires dynamic calculation of thermal profile during the simulation of recording process. We have developed this particular capability and are adding it to our system simulation model at the moment.

In particular, we will study (1) effect of pulse rate and (2) effect of pulse duty cycle. The heating intensity will be varied accordingly. Pulse laser operation certainly improves reliability of near field transducer, but also could bring improved recording performance due to the added tunability of the resulted heating in medium could very well yield more optimized recording process. The recording will be evaluated in terms of the medium SNR of the recorded bits at various linear and track densities, especially around the targeted area densities.

3. Impact of medium magnetic properties near Curie temperature

Temperature dependences of magnetic properties, such as crystalline anisotropy field, near Curie temperature are of great importance to recording performance characteristics. Moreover, spatial distributions, i.e. grain-to-grain variation, of these properties are equally important as well.

It is important to obtain experimental measurements of the temperature dependence of these parameters near Curie temperature. At DSSC, we are setting up such measurement capability so that we can have direct measurement data on some of the potential HAMR media, such as FePt-$L1_0$. The obtained data can be directly used in modeling to calculate the corresponding recording performance and resulting medium SNR at various linear and track densities. This combined experimental and modeling study will enable us to evaluate the status and capability of current media and identify possible shortfalls in the media. Thus provide valuable guidelines to medium improvement/development. We also plan to work with any medium team under ASTC to obtain the much needed experimental measurement data.

One of the measurement capabilities that we are setting up is the measurement of anisotropy field as a function of temperature. We have a PPMS system with a VSM head and a maximum perpendicular field at 6Tesla. We are setting up an heating-oven that will enable us to do measurement at temperatures ranging from RT up to 1000 ^{o}K. We also plan to combine the hysteresis measurement with MFM measurement so that spatial magnetization fluctuation of the sample after experiencing a given field at a given temperature can be quantitatively characterized. Combining the designed measurements with corresponding modeling, we should be able to identify quantitatively all the parameters listed in the table below, which are critically important for performing the system design analysis to be described in the next section.

Table 1. Input parameters need to be determined by designed measurements

Parameter	Mean value	Distribution	σ	Temperature Dependence
Grain Size	$\overline{D}$	Lognormal/Gaussian	ΔD	No
Anisotropy Field	$\overline{H}_K$	Bipolar/Gaussian	ΔH_K	Yes
Damping	α	Gaussian	$\Delta\alpha$	Yes
Dephasing Time	T_2	Gaussian	ΔT_2	Yes
Reversal Time	T_1	Gaussian	ΔT_1	Yes
Curie Point	T_C	Gaussian	ΔT_C	N/A
Magnetization	M_S	Gaussian	ΔM_S	On T_C

4. System Design Modeling for Target Area Densities

With the above study, we would be able to gain a solid foundation for HAMR system modeling. With such capability, we plan to perform a system modeling for providing guidelines to system design for achieving the target area densities. The evaluation criteria include the following:

a) Medium recording SNR at given linear and track densities.

b) Edge erasure/writing characteristics at required track densities.

c) Maximum temperature in the medium during recording processes.

The modeling will start from the system design parameter set that we obtained with previous INSIC-EHDR/IDEMA-ASTC funded work. We will first focus on the parameters list in the above table to explore the requirements for each of the parameters listed.

We plan to work closely with other teams in this collective research activity to communicate our simulation results and get feedback to see if recording can be optimized with practical constraints. In particular, we will work with *medium development team* to get a good understanding of the critical microstructure and magnetic characteristics, like the parameters listed in the table in the previous section. We will also work with *the transducer team* to obtain the actual heating profile in the medium as well as novel schemes such as pulse heating operation. We also plan to work with *the channel team* to provide the simulated recording patterns and readback waveforms with noise characteristics.

One of the objectives is to obtain a full set of system parameters and their range of distributions for achieving target area recording density. This set of parameters will include requirements for

- medium magnetic properties
- medium thermal properties
- head-medium-spacing
- near-field-transducer generated thermal profile
- read head characteristics, both in down-track and cross-track directions
- channel capability

This set of parameters will be provided to the ASTC roadmap team as well as all other related teams. During the course of research, feedback will be collected to reiterate analysis to make the analysis more practical and reasonable. We will update the HAMR system investigation as more information becomes available with the publishing of the ASTC roadmap.

5. Analysis and Characterization of Recording and Noise for On-Track and Track Edges

Another important objective of this proposed study is to obtain recording characteristics, e.g. jitter noise characteristics, data dependent transition shift, track edge properties, etc, that could be very useful for HAMR channel team for developing optimized data recovery channel for HAMR system. Simulated recorded bits/transitions will be analyzed and characterized to provide detailed characteristics for the following performance parameters:

- Transition properties, including on-track sharpness and cross-track profiled
- Transition noise characteristics: position jitter and amplitude variation
- Track edge characteristics
- Impact of medium properties
- Impact of heat-profile properties
- Impact of HMS and HMS variation

The obtained characteristics will be transmitted to other related ASTC teams.

Personnel

One Ph.D. graduate student of ECE will conduct this research full time. Professor Jimmy Zhu will supervise the student as well as directly participating in the proposed research.

Jian-Gang (Jimmy) Zhu is the ABB Professor of Electrical and Computer Engineering and the Director of the Data Storage Systems Center at Carnegie Mellon University. He is a courtesy professor in the Department of Material Science and Engineering and a courtesy professor in the Department of Physics. Dr. Zhu received Ph.D. degree in Physics from the University of California at San Diego in 1989. He had been a faculty member in the Department of Electrical

Engineering at University of Minnesota from 1990 to 1996 prior to joining the faculty at Carnegie Mellon University in 1997. Dr. Zhu's research has been in the field of magnetic data storage technologies, and his work on the microstructure of thin film recording media has been pivotal for hard disk drives to reach today's storage capacity. He has pioneered the research on utilizing micromagnetic modeling for MRAM memory design and established some of the most fundamental design principles used today. He has authored or co-authored over 250 major technical journal papers, written six book chapters, and given over 70 invited papers at major international conferences. He holds fifteen U.S. patents. Over the years, Dr. Zhu has received many awards, among them: National Science Foundation Presidential Young Investigator Award in 1993, the McKnight Land Grant Professorship from the University Minnesota Board of Regents in 1993, the R&D100 Award in 1996, IEEE Distinguished Lecturer in 2004, the Outstanding Research Award from Carnegie Mellon in 2010, and IEEE Magnetic Society Achievement Award in 2011. Dr. Zhu served on the Advisory Editorial Board for the Journal of Magnetism and Magnetic Materials, North-Holland, Elsevier from 1998 to 2008. He is a fellow of IEEE.

Budget Plan

ITEM	JUSTIFICATION	BASE	TOTAL
i. Overhead	**Facilities and Administration:** Overhead on this proposal has been calculated at our current proposed or negotiated non-federal rate for all fiscal years. The modified total direct cost base (MTDC) amount used in calculating the indirect costs is the total direct costs, excluding equipment, capital expenditures, charges for tuition remission, rental costs, scholarships and fellowships, internally charged telephone, internally charged copying, and individual subcontract costs in excess of $25,000. The current non-federal rate is 63%.	63% of $33,620 (MTDC)	$20,992
ii. Direct Project Cost	**Computing Facility Fees:** The Carnegie Institute of Technology (College of Engineering) maintains its own computing facility and is not dependent on the university maintained facility. Included in the support cost of our facilities are the costs associated with networking, systems software support, time-shared machines, printing, maintenance contracts, and salaries of the facility staff, including computer operators, systems programmers, systems engineers, line technicians, and repair technicians. Facilities maintenance costs for the PI's projects were derived from a comparison of Computing Facilities Support expenditures to research salaries and fringe benefits.	$2,000 per graduate student	$2,000
iii. Facility use fees	N/A		$0
iv. Materials	N/A		$0
v. Student Stipend/ Tuition	**Graduate Student Support:** Stipend and tuition amounts are based on FY 2012 proposed rates. Graduate support is increased effective September 1. The colleges each set their graduate support rates in consultation with their faculty, department heads, deans and the Provost taking into account an evaluation of our historical market position in comparison to our	Stipend: $2,360 x 12 mos = $28,320 Tuition/fee: Full Academic	$66,270

	peer institutions. Salaries for graduate students are based on a nine month academic year and three summer months. We are requesting one year of full tuition and stipend support for one graduate student researcher.	Year support (9 mos) = $37,950	
vi. Travel	**Domestic Travel:** Travel will include attendance by the PI at ASTC/sponsor specific meetings. Educational Institutions are not subject to the Federal Civilian Employee and Contractor Travel Expense Act of 1985 (Pub. L. 99-234) at this time. Costs incurred for travel, including lodging and other subsistence, will be considered reasonable and allowable to the extent that they do not exceed charges normally allowed by the University in its regular operations according to institutional policy. In the absence on institutional policy, the GSA rates shall apply.	3 west coast trips @ $1,000 per trip	$3,000
TOTAL REQUESTED			$92,262