SAMSI 2007-08 Program on Random Media
Final Report

1 Introduction

Random media is a classical field which is presently receiving widespread attention as new theory, approximation techniques, and computational capabilities are applied to emerging applications. Due to the breadth of the field, its inherent deterministic, stochastic and applied components have typically been investigated in isolation. However, it is increasingly recognized that these components are inexorably coupled and that synergistic investigations are necessary to provide significant fundamental and technological advances in the field. The SAMSI Program on Random Media provided a forum to investigate statistical and deterministic components of random media for applications.

The goal of the program was to bring together researchers investigating a variety of phenomena pertaining to random media. Specific research directions were drawn from the following topics: random media including scattering theory in highly discontinuous and random media, time reversal, interface problems, imaging problems, scattering theory, porous Media, imaging in random media and related applications. The program addressed a number of fundamental issues in model development, analysis, and numerical approximation. The inherent synergy between deterministic, statistical, and physical analysis necessitates a concerted collaboration between applied mathematicians, statisticians, engineers, geologists, and material scientists which is too often absent but is necessary to provide fundamental advances to the field.

2 Program Organization

2.1 Program Leaders

The program leaders were Russel Caflisch (UCLA), Maarten De Hoop (Purdue University – co-Chair), Rick Durrett (Cornell University – NAC Liaison), Weinan E (Princeton University), Josselin Garnier (Universite Paris VII), William Kath (Northwestern University), George Papanicolaou (Stanford University), Lenya Ryzhik (University of Chicago), Ralph Smith (SAMSI, Directorate Liaison), Chrysoula Tsogka (University of Chicago), Eric Vanden-Eijnden (NYU), Jack Xin (UC Irvine), Wojbor Woyczynski (Case Western Reserve University), and Hongkai Zhao (UC Irvine – co-Chair).

2.2 Local organizers:

The following individuals were the main local organizers for the program: Kazufumi Ito, Zhilin Li, and Ralph Smith, all from North Carolina State University.

2.3 Major Participants

Long and Short Term Visitors: The following individuals spent between a month and semester at SAMSI participating in the program: Yu Chen (Courant Institute, New York University), Laurent Demanet (Stanford), Maarten De Hoop (Purdue University), Josselin Garnier (Paris VII), Isaac Klapper (Montana State University), Xiaofan Li (Illinois Institute of Technology), John Strain (UC Berkeley), Hongkai Zhao (UC Irvine), Guowei He (Iowa State University and Chinese Academy of Science, short term), Ping Lin (University of Dundee, UK, short term).

Postdoctoral Fellows: Elaine Spiller (Mathematics, SUNY-Buffalo), Weigang Zhong (Mathematics, Maryland).

Graduate Students: Qunlei Jiang (North Carolina State University), Brandon Lindley (University of North Carolina), Hui Xie (North Carolina State University), Ke Xu (University of North Carolina), Jason Wilson (Duke University), Sarah Olson (North Carolina State University), Elizabeth Bouzarth (University of North Carolina), Qin Zhang (North Carolina State University).

Other Participants: Jinru Chen, Yushun Wang (Visiting scholar, North Carolina State University), Zhonghua Qiao (postdoc at North Carolina State University), Martin Hiller (North Carolina State University).

Faculty Releases: Tom Beale (Mathematics, NCSU), Greg Forest (Mathematics, UNC), Kazi Ito (Mathematics, NCSU), Chuanshu Ji (Statistics, UNC), Zhilin Li (Mathematics, NCSU), Mauro Maggioni (Mathematics, Duke).

2.4 Working Groups

The working groups met weekly either throughout the year or in the Fall semester, 2007, to pursue their particular research topics. These were identified in the kickoff and midprogram workshops and/or subsequently chosen by the working group participants. A few working groups had their activity concentrated in a shorter period of time. As usual at SAMSI, the working groups consist of SAMSI visitors, postdoctoral fellows, graduate students, and local faculty and scientists. A number of working group members did not reside at SAMSI nor in the area, and took active part on the meetings via teleconferencing and Webex access. The working groups had active web pages in which material, notes, agendas and members were regularly posted.

Heterogeneity in Biological Materials: Led by Greg Forest(UNC)

The active participants were Greg Forest (UNC), Weigang Zhong (SAMSI), Isaac Klapper (Montana State), Brandon Lindley (UNC), Ke Xu (UNC), Elizabeth Bouzarth (UNC). Scott McKinley (Duke), Mircea Grigoriu (Cornell), Lingxing Yao (UNC), Mansoor Haider (NCSU), Chuanshu Ji (UNC), Lisa Fauci (Tulane remote), Robert Dillon (Washington State), and Christel Hohenegger (NYU).

Stochastic PDE: Led by Kazufumi Ito (NCSU)

The participants were Jim Berger (Duke and SAMSI), Mircea Grigoriu (Cornell), Martin Hiller (SAMSI/NCSU), Kazufumi Ito (NCSU), Min Kang (NCSU), Shengtai Li (Los Alamos), Elaine Spiller (SAMSI), John Strain (UC-Berkeley), Yimin Xiao (Michigan State), Jack Xin (UC-Irvine), Qin Zhang (NCSU).

Interface Problems: Led by Thomas Beale (Duke) and Zhilin Li (NCSU)

The participants were Thomas Beale (Duke), Jinru Chen (NCSU & China), Kazufumi Ito (NCSU), Qunlei Jiang (NCSU) , Isaac Klapper (Montana State), Xiaofan Li (IIT), Zhilin Li (NCSU), Zhonghua Qiao (NCSU), John Strain (UC-Berkeley), Jason Wilson (Duke), Hui Xie (NCSU), Wenjun Ying (Duke), Qin Zhang (NCSU), Hongkai Zhao (UC-Irvine), Weigang Zhong (SAMSI & NCSU).

Waves and Imaging: Led by Laurent Demanet (Stanford) and Maarten de Hoop (Purdue)

The participants were Yu Chen (NYU), Laurent Demanet (Stanford), Maarten de Hoop (Purdue), Kazufumi Ito (NCSU), Mauro Maggioni (Duke), Vahagn Manukian (NCSU), Yvonne Ou (UCF), Hongkai Zhao (UC-Irvine).

3 Research Foci

The SAMSI Program on Random Media provided a forum to investigate statistical and deterministic components of random media for applications including, but not limited to, time reversal, interface problems, imaging in random media, and scattering theory for discontinuous media.

Time Reversal: The component on time reversal built upon recent analysis and experimental observations that time reversal of waves propagating in disordered media permit refocusing. This somewhat unexpected property has profound ramifications in domains such as wireless communications, medical imaging, nondestructive evaluation, and underwater acoustics. Whereas the behavior of one-dimensional acoustic waves is mathematically and statistically understood, questions regarding multidimensional media remain widely open with the exception of the baraxial wave equation.

Interface Problems: Interface problems arise in a diverse range of applications including multiphase flows and phase transitions in fluid mechanics, thin film and crystal growth simulations in material science, and mathematical biology problems modeled by partial differential equations involving moving fronts. In computational fluid dynamics, electromagnetic scattering and ground water flows, efficient numerical approximation are essential for quantifying the effective property of the medium due to fluctuating inhomogeneous and random medium. The level set method has proven to be an extremely versatile tool for tracking deformations in shape geometries, moving interfaces, and free boundaries in a number of related applications, and one facet of the program will focus on extensions of this approach to include the effects of random media and stochastic processes. Other aspects of the interface component will focus on modeling and analysis of random interface growth processes including crystal growth and solidification, Monte-Carlo Wiener-Chaos expansion and homogenization methods for stochastic partial differential equations, and level set methods and Lagrangian formulations (particle approaches) for random media simulations.

Imaging: Imaging problems in random media arise in a number of applications including biomedical imaging and seismic analysis. In the latter category, a detailed knowledge of earth medium heterogeneities is necessary for oil and gas recovery, earthquake and volcanic predictions, and environmental analysis. One fundamental issue involves the multiscale relation between large scale structures, which are considered as deterministic, and small scale heterogeneities which are considered to be random fluctuations form the deterministic structures. A related issue concerns the analysis of coupled processes.

Scattering Theory: Whereas mathematical scattering theory for one-dimensional regimes is fairly mature, little of the analysis extends to multidimensional media with the exception of the baraxial wave equation. Hence this facet will focus primarily on the development of theory, numerical methods and validation techniques pertaining to scattering theory for multidimensional media.

4 Specific Activities and Publications

4.1 Heterogeneity in Biological Materials Working Group

The working group on Heterogeneity in Biological Materials developed a variety of focused projects that continue to the present. The projects were driven by applications to lung biology and biofilms, where mucus and related viscoelastic materials play vital functions. The most exciting outcome is the broad project on adapting the ideas of the immersed boundary method as a means to impose microstructure throughout a complex fluid. This investigation is not yet complete, but significant progress has been made.

Additional collaborative projects that arose from the working group and are being actively pursued include one on stochastic methods for diffusive transport, including inverse characterization from experimental data and mean passage time for anomalous diffusion, and a second on new numerical methods for heterogeneous biological media that merge the immersed boundary method and fluid solvers. These collaborations involve participants that are local and remote (the latter being Lisa Fauci, Robert Dillon, Isaac Klapper, and Mircea Grigoriu).

The working group on Heterogeneity in Biological Materials has a number of consequences to report:

- Based on a collaboration started at SAMSI between applied mathematicians, probabilists and statisticians, Scott McKinley (Duke), Lingxing Yao (Utah), Christel Hohenegger (NYU-Courant), Tim Elston (UNC), John Fricks (Penn State), and Gustavo Didier (Tulane) submitted an FRG to NSF-DMS on "Viscoelastic Diffusion". The proposal is still pending.
- SAMSI Graduate RAs Ke Xu and Brandon Lindley (advised by Forest) both have published papers leading to their primary thesis results. Ke graduates August, 2009 and she worked with Isaac Klapper (Montana State) while he visited SAMSI. Brandon graduated in May 08 and took a position at U. South Carolina to work on biofilms, a topic he was introduced to at SAMSI.
- Greg Forest and H. Zhou (Naval Postgraduate School) organized a mini-symposium at the SIAM annual meeting in San Diego this past summer 08 on research from the working group.
- Greg Forest and Qi Wang organized a minisymposium at the SIAM Computational Sciences and Engineering meeting in Miami, Fl on complex fluids, attended by Lisa Fauci, Robert Dillon and grad students and postdocs from our working group.
- Mansoor Haider and Greg Forest followed up on their working group to organize a large minisymposium at the regional AMS meeting at NC State on April 4-5, 2009, again attended by members of the SAMSI working group (Hohenegger, McKinley).
- Greg Forest, Brandon Lindley and Qi Wang organized a minisymposium at the regional SIAM meeting in Columbia, SC on April 4-5 on complex fluids, attended by members of the SAMSI working group.
- Weigang Zhong was introduced to the Immersed Boundary method in our working group. He contacted Boyce Griffith at NYU by recommendation of Lisa Fauci, and learned how to use the parallel IB code. His new job at Corning, Inc. is on problems that are proprietary, but related to the IB method.

Publications:

1. D.B. Hill, B. Lindley, M.G. Forest, R. Superfine, S. Mitran, *Experimental and modeling protocols for a micro-parallel plate rheometer*, UNC preprint, to be submitted.

2. C. Hohenegger, M.G. Forest, *Two-point microrheology, II: simulation protocols*, UNC-NYU preprint, to be submitted.

3. Scott A. McKinley, Lingxing Yao and M. Gregory Forest, *Transient Anomalous Diffusion of Tracer Particles in Soft Matter*, Duke-UNC preprint, to be submitted.

4. J. Fricks, L. Yao, T. Elston, M.G. Forest, *Time-domain methods for passive microrheology and anomalous diffusive transport in soft matter*, SIAM J. Appl. Math., Vol. 69(5), 1277-1308 (2009).

5. E. Howell, B. Smith, G. Rubinstein, M.G. Forest, B. Lindley, D. Hill, R. Superfine, S. Mitran, *Stress communication and filtering of viscoelastic layers in oscillatory shear*, J. Non-Newtonian Fluid Mechanics, Vol. 156, 112-120 (2009).

6. C. Hohenegger, M.G. Forest, *Modeling aspects of two-bead microrheology*, Proceedings of XVth International Congress on Rheology, Springer, August, 2008, AIP Conference Proceedings, Materials Physics & Applications Series, Vol. 1027 (2008).

7. C. Hohenegger, M.G. Forest, *Two-point microrheology: modeling protocols*, Phys. Rev. E 78, 031501 (2008).

8. S. Mitran, M.G. Forest, B. Lindley, L. Yao, D. Hill, *Extensions of the Ferry shear wave model for active linear and nonlinear microrheology*, J. Non-Newtonian Fluid Mechanics Vol. 154:120-135 (2008).

9. C. Hohenegger, M.G. Forest, *Direct and Inverse Modeling for Stochastic Data in Microbead Rheology*, Proceedings in Applied Mathematics and Mechanics (PAMM), Special Issue: Sixth International Congress on Industrial Applied Mathematics (ICIAM07) and GAMM Annual Meeting, Zrich 2007, Published Online: Oct 30 (2008).

4.2 Stochastic PDE Working Group

This working group held several meetings over the Fall of 2007, and Spring 2008.

The Stochastic PDE working group had weekly meetings and discussed joint collaborations and works on Random Field Theory and its applications in Communications and Image Classification. Specifically, the following topics were discussed and presented

- the existence of solutions to the stochastic heat and wave equations with non-Lipschitz but monotone nonlinearity and the temporal and special statistic properties of solutions based using the random field theory,
- the fiber communication system modelled by the randomly perturbed dispersion-managed nonlinear Schroedinger and using the corresponding soliton solutions,
- the interacting particle system and applications to network communications and data flow analysis.

The students associated to the working group worked on three specific projects. Over the Spring 2008 semester, presentations were given for each of these projects.

The first project entailed classification of a random surface based on the random pattern. The motivation comes from steel fabrication. When a sheet of steel is fabricated, it is often far from perfect. In flawed regions, the molecular arrangement may differ from the ideal steel regions. The molecular patterns of the steel appear to have very little structure and a homogenous appearance similar to noise. After viewing the random pattern present in the flawed steel, and the pattern present in the good steel, it becomes apparent that these regions have a different random pattern. The flawed steel appears to have a more heterogeneous mixing pattern than the good portions have. Leveraging this insight, we focused on discriminating between the two regions based on local covariance statistics then classifying based on classification trees. Of particular interest in the study are the vector autoregressive statistics.

The second project involved simulations of some interacting particle systems. To begin with, we simulated the Totally Asymmetric k-Exclusion Process. The dual of the results of the simulations were then used to test the theoretical upper and lower bounds in hopes of finding more precise bounds for the process.

The third project dealt with quantum probability theory, quantum filtering theory, and the stabilizing feedback control for quantum spin systems. Based on the quantum filtering theory, our focus was to construct a stabilizing continuous feedback control for quantum filtering equation in quantum spin systems.

Publication: K. Ito et al., *Multi-valued Stochastic Evolution Equations in Hilbert Spaces and Integrable Solution*, in preparation.

4.3 Interface Problems Working Group

This group held regular meetings over the Fall of 2007, and Spring 2008. A web page

`http://www.samsi.info/200708/ranmedia/wg/het-random/if-index.html`

describes the topics covered and some presentations for the working group:

- Introductions of the boundary integral method and level set method
- Introductions of the level set method
- Immersed interface method
- Kernel-free boundary integral method
- Grid-based particle method for moving interface problems
- Problems with incompressible interfaces
- Fluid mixed model of tissue deformations
- Modified bilinear interpolation and FEM for an elliptic interface problem

The working group worked on moving interface free boundary problems. Different ideas and approaches, such as boundary integral method, level set method, immersed interface method, immersed boundary method, and other related topics were thoroughly examined and assessed. The weekly group meetings were very interactive and candid. New collaborations and new ideas were generated. For examples, new methods based on combining different approaches to complement each

other's strengths and weaknesses have been proposed and are going to be implemented. The current project including the grid based particle method for moving interface free boundary problems; numerical methods and models for incompressible membranes with bending.

Much of the research focused on analysis of fundamental questions of fluid motion and design and analysis of numerical methods for fluids, and especially methods for problems with interfaces. The Working Group on Interface Problems connected directly with several research interests. Because several of participants had overlapping expertise, we had a great deal to discuss in detail in understanding the advantages and limitations of existing methods and how to push them further toward more realistic problems. However, Dr. T. Beale's expertise is weighted more toward analysis, as opposed to practical computational methods, in comparison with other active participants. It has been valuable to the participants to learn better what is currently being done, what works well in practice, and what does not. Conversely, some analytical point of view contributed to qualitative understanding of behavior of numerical methods, especially the qualitative nature of errors.

Publications:

1. Jun Wang, Qin Cai, Zhilin Li, Hong-Kai Zhao, and Ray Luo, Achieving energy conservation in PoissonBoltzmann molecular dynamics: Accuracy and precision with finite-difference algorithms, Chemical Physics Letters, Volume 468, Issues 4-6, 22 January 2009, Pages 112-118.

2. K. Ito, M. Lai, and Zhilin Li, A well-conditioned augmented system for solving NavierStokes equations in irregular domains, J. Comput. Phys. (2009), doi:10.1016/j.jcp.2008.12.028.

3. X. Wan, Z. Li, and S. Lubkin, Mechanics of mesenchymal contribution to clefting force in branching morphogenesis, Biomechanics and Modeling in Mechanobiology, Vol. 7, 417-426, 2008.

4. H. Xie, K. Ito, Z. Li, J. Toivanen, A finite element method for interface problems with locally modified triangulations, AMS Contemporary Mathematics, Vol. 466, 2008, 179-190.

5. Q. Jiang, Z. Li, and S. Lubkin, Theoretical & numerical analysis for a fluid mixure model of tissue deformation, Comm. in Comput. Phy. Vol. 3, 620-634, 2009.

4.4 Waves and Imaging Working Group

This group held regular meetings over the Fall of 2007 with activities summarized on the webpage `http://www.samsi.info/200708/ranmedia/wg/imaging-random/imaging-index.html`

In the group on Waves and Imaging, a range of collaborations were established. Yvonne Ou from U. Central Florida teamed with Jean-Pierre Fouque and Josselin Garnier to investigate the problem of time-reversal for elastic waves. They started with a review of the literature in the group meeting very soon. Gabriel Peyre from U. Paris-Dauphine teamed up with Laurent Demanet to investigate methods of compressive wave computations, with application to migration. Sava Dediu from NCSU joined with Laurent Demanet to study an optimal-transport approach to the problem of model velocity estimation in one-dimensional seismic inversion. All three collaborations could not have been initiated without the support of SAMSI, and actively benefit from the teleconferencing capabilities that the working room offers. The research produced by the weekly group meeting were the basis for the two discussion sessions in the "Waves and Imaging" workshop.

One of the outcomes of the"Waves and Imaging" working group is the collaboration between Laurent Demanet and Gabriel Peyre on "Compressive wave computation", a novel method for efficiently solving wave equations in the context of inverse problems in seismology. The backdrop for this effort

was the group meeting's extensive discussion on nonlinear sampling strategies in imaging, including compressed sensing, during the Fall of 2007. What became apparent is that the ideas of sparsity and undersampling suggest an entirely different strategy for simulating linear wave phenomena on a large computational scale, using nonlinear synthesis from a few eigenfunctions of the Helmholtz operator, chosen at random. The main mathematical question concerned the number of such eigenfunctions needed for a given accuracy guarantee, and was solved during the random media program. Under mild assumptions, the answer is a remarkable O(log(N)) where N is the desired resolution. Gabriel Peyre's visit in November benefited from generous SAMSI funding and was instrumental in establishing the numerical validity and applicability of this result. In March 2008, the project reached a first milestone with the completion of a preprint treating the one-dimensional case. More collaborators will join our effort as the potential impact of this discovery in reflection seismology is now clear: the compressive viewpoint yields embarrassingly parallel algorithms that promise to help rethink the main computational bottlenecks of adjoint-state methods on large CPU clusters. The inception of this project would not have been possible without the SAMSI Random Media Program and the focus it provided. In fact we would probably not even have thought of starting this project were it not for the opportunity provided by the SAMSI program. Finally, Ray Luo, who is a faculty member in Molecular Biology & Biochemistry at UCI, was invited to the moving interface workshop during the SAMSI program. As part of the program, Luo, Zhilin Li and Hongkai Zhao initiated a project on protein folding mechanism and structure prediction. This work is ongoing and covers the application of efficient numerical methods to study biomolecular structures, functions, and intermolecular interactions at atomic detail and as well as the application of the methods under construction to understand and predict the relations between the sequences, structures and functions of these molecules.

Publications:

1. Laurent Demanet and Gabriel Peyre, *Compressive Wave Computation*, submitted, 2008.

2. Semyon Tsynkov, *On SAR imaging through the Earth Ionosphere*, SIAM Journal on Imaging Sciences, 2 (2009) No. 1, pp. 140–182.

3. Shingyu Leung and Hongkai Zhao, *A New Grid-Based Particle Method for Interface Problems*, Journal of Computational Physics, Volume 228, Issue 8, 2009.

4. Shingyu Leung and Hongkai Zhao, *A Grid Based Particle Method for Evolution of Open Curves and Surfaces*, UCLA-CAM 08-72. Submitted.

5. Jun Wang, Qing Cai, Zhilin Li, Hongkai Zhao, and Ray Luo, *Achieving Energy Conservation in Poisson-Boltzmann Molecular Dynamics: Accuracy and Precision with Finite-Difference Algorithms*, to appear in Chemical Physics Letters.

6. Qin Cai, Jun Wang, Hongkai Zhao, and Ray Luo, *On Removal of Charge Singularity in Poisson-Boltzmann Equation*, to appear in Journal of Chemical Physics.

5 Workshops

5.1 Opening Workshop

The Opening Workshop for the SAMSI program on Random Media was held Sunday-Wednesday, September 23-26, 2007, at the Radisson Hotel RTP in Research Triangle Park, NC. It was preceded, on Sunday, September 23, with tutorials by Eric Vanden-Eijnden (NYU), and Jack Xin (UC- Irvine).

The goal of the opening workshop was focused on the formulation of challenges and directions to be pursued during the Random Media Program. Focus areas during the program included the following topics: time reversal, interface problems, imaging problems, scattering theory, heterogeneity in biological media, and porous media. During the workshop, several working groups for the program were formed to promote engagement (via web or teleconference) of those who will not be in residence at SAMSI during the program. The workshop engaged a broadly representative segment of the mathematical, statistical and disciplinary sciences.

The workshop was organized by Maarten De Hoop (Purdue University), Zhilin Li (North Carolina State University), Ralph Smith (SAMSI, Directorate Liaison), Hongkai Zhao (UC Irvine).

The workshop included a number of distinguished speakers and young researchers: John Cushman (Purdue University), Weinan E (Princeton University) , Bjorn Enquist (Univ. of Texas-Austin), Lisa Fauci (Tulane University), Jean-Pierre Fouque (Univ. of California, Santa Barbara), Tom Hou (California Institute of Technology), Sam Kou (Harvard University), Karl Kunisch (University of Graz), Randy LeVeque (University of Washington), John Lowengrub (Univ. of California-Irvine), Stanislav Molchanov (UNC Charlotte), Gretar Tryggvason (Worcester Polytechnic Institute), Gunther Uhlmann (University of Washington), Wojbor Woyczynski (Case Western Reserve University); and young researchers: Karen Daniels (NC State), John Fricks (Penn State), Lucy Zhang (Rensselaer Polytechnic Institute), Lucy Zhang (Rensselaer Polytechnic Institute).

During the opening workshop, two panel discussions were conducted. The first one was on interface problems chaired by Gretar Tryggvason (WPI) and Bjorn Enquist (UT Austin). The second one was on time reversal, Stochastic PDEs, and imaging, chaired by Jean-Pierre Fouque (UC Santa Barbara) and Maarten De Hoop (Purdue). A first iteration on the working groups was made. After discussions before the end of the workshop, a list of working groups was formed and the participants signed up for groups of interest. There was an extraordinary response to the working group call, with almost all of the workshop participants remaining for the working group formation.

5.2 Interface Workshop

The interface workshop was held on November 15-16, 2007 at the Radisson Hotel RTP in Research Triangle Park, NC.

The theme of the workshop focused on interface problems. In many science and engineering problems, multiphase systems that involve moving interface and free boundary are quite challenging for both mathematical analysis and numerical simulations. One of the main difficulties is the coupling of the evolution and geometry of the interface with the global dynamics of the bulk. The coupling is often nonlinear and non-local. Singularities, such as discontinuity of material properties and physical quantities across the interface, and topological changes, such as merging and pinch-off, occur during the evolution. Further complications, such as surface diffusion, random media, and multiple scales, can make the problem even more challenging.

Recently there has been significant progress in both theory and numerical methods for moving interface problems. In this workshop, experts from different backgrounds will address aspects of modeling, theory, numeric and applications and their integration. The emphasis in the workshop is to foster discussions, collaborations, identification of new problems in a cross-disciplinary setting, concentrating on numerical methods, analysis, modeling, and applications of interface problems. The workshop was organized by Zhilin Li (NCSU), Ralph Smith (SAMSI, Directorate Liaison), and Hongkai Zhao (UC-Irvine).

The speakers of the workshop included: Shi Jin (University of Wisconsin-Madison), Jon Wilkening, (University of California-Berkeley), Mark Sussman (Florida State University), Ray Luo (University of California-Irvine), Sigal Gottlieb (University of Massachusetts, Dartmouth), Ping Lin (Uni-

versity of Dundee & National University of Singapore), Patrick Guidotti (University of California-Irvine), J. Thomas Beale (Duke University), Hongkai Zhao (University of California-Irvine), John Strain (University of California-Berkeley), Robert Dillon (Washington State University), Guowei He (Iowa State University), David Chopp (Northwestern University), Richard Tsai (University of Texas-Austin), and Alina Chertock (North Carolina State University).

5.3 Waves and Imaging Workshop

The Waves and Imaging workshop was held on January 31 and February 1, 2008, at the Radisson hotel in Research Triangle Park, NC. A few new approaches have been recently proposed to solve the challenging problems of imaging and inversion from wave measurements, most notably in geophysics and optics. A first example is time reversal, where flipped waveforms sent back into a random medium refocus an order of magnitude better than they would in a uniform medium. A second example is cross-correlation of seismic noise, a procedure that produces the entire Green's function of surface waves from passive receivers. A third example is compressive reverse-time migration where ideas from compressive sampling bring the computational complexity of migration down to the information level of seismic wave fields. The explanation and prediction of all these phenomena stem from some surprising results of statistical stability and probability concentration, which are currently being researched by several groups. The main objectives of this workshop are to: (1), review the extent to which these imaging methods have been developed and understood; (2) expose the progress made in the working group, and (3) discuss open problems and future directions. The workshop was organized by Laurent Demanet (Stanford), Maarten de Hoop (Purdue), Kazufumi Ito and Zhilin Li (NCSU).

The speakers of the workshop included: Margaret Cheney (Rensselaer Polytechnic Institute), Gang Bao (Michigan State University), Yu Chen (New York University), Richard Weaver (University of Illinois at Urbana-Champaign), Luis Tenorio (Colorado School of Mines), Lenya Ryzhik (University of Chicago), Josselin Garnier (Université de Paris VI), Knut Solna (University of California-Irvine), Liliana Borcea (Rice University), William Symes (Rice University), Henri Calandra (Total Corporation), John Schotland (University of Pennsylvania).

5.4 Transition workshop:

This will be held on May 1-2, 2008, at the Radisson hotel in Research Triangle Park, NC. The workshop was organized by Maarten de Hoop (Purdue University), Zhilin Li (North Carolina State University), Ralph Smith (North Carolina State University, SAMSI Directorate Liaison), Hongkai Zhao (UC-Irvine). The goals of this workshop were to

1. Present results generated by this SAMSI program to the applied mathematics, statistics and engineering communities.

2. Formulate follow-up plans for this SAMSI program to continue research and education in this interdisciplinary area.

Several of the speakers presented overview talks about the projects spawned during the program and the significant challenges that remain. For instance, new numerical methods for heterogeneous biological media that merge the immersed boundary method and fluid solvers were discussed. Exciting novel numerical techniques for interfacial free boundary problems involving viscous fluids were also exposed and discussed. Examples of these include hybrid numerical methods that incorporate a

separate analytical reduction of the dynamics within the transition layer into a full numerical solution of the interfacial free boundary problem.

The speakers of the workshop included: Greg Forest (University of North Carolina, Chapel Hill), Kazufumi Ito (North Carolina State University), Min Kang (North Carolina State University), Chiu-Yen Kao (Ohio State University), Taufiquar Khan (Clemson University), Isaac Klapper (Montana State University), Anita Layton (Duke University), John Lowengrub (University of California, Irvine), Li-Shi Luo (Old Dominion University), Michael Siegel (New Jersey Institute of Technology), Jason Wilson (Duke University).

6 Education and Outreach

6.1 Credit Courses

The Program offered one 3 credit course in the 2007 Fall semester. The title of the course was "Numerical Methods for Free Boundary and Moving Interface Problems" and the instructors were Kazufumi Ito (NCSU), Zhilin Li (NCSU), and Hongkai Zhao (UC Irvine). Nine students registered in this class including four females. There were about four additional postdocs from SAMSI and NCSU who audited the class.

6.2 SAMSI Two-Day Undergraduate Workshops

February 29-March 1, 2008 at SAMSI. Twenty four undergraduate students from undergraduate colleges and universities across the nation participated in this workshop.

In the workshop, K. Ito (NCSU) presented two lectures on respectively "Level Set Method and Applications" and "Central Voronoi Tesselation and Applications." H. Zhao (UCI) gave two lectures as well on "Wave Propagation" and "Imaging Using Waves."

The workshop exposed the students to the idea of mathematical models and their numerical computer implementation, in a wide variety of scenarios and at a level adequate for the wide range of students present. Hands-on computer tutorials helped students grasp the basics of the level set method, wave propagation in random media, and imaging process. Significant emphasis was put on open and often spirited discussions. The workshop was very well attended with students from all over United States. The Workshop accomplished the goals of exposing and interesting a wide diversity of bright students to the area of Random Media, their development, assessment and utilization.

6.3 Graduate students.

The Program contributed to the achievements, education, and Ph.D. projects of many graduate students.

Brandon Lindley (UNC) Brandon Lindley was introduced to biofilms through his participation to the SAMSI program. Brandon graduated in May 08 and took a position at U. South Carolina to work on that topic.

Jason Wilson (Duke) was involved in the interface working group. Jason Wilson is a graduate student at Duke working toward his Ph.D. He was supported by SAMSI for the fall semester, 2007. He took the course in the fall on free boundaries and moving interfaces. His thesis focuses on the construction of overlapping coordinate grids with low distortion on a given, smooth, closed surface in three dimensions. His work has applications to boundary integral methods. While presenting

some similarities with the work of Shing-Yu Leung and Hongkai Zhao, Jason's method uses a more detailed representation of the surface which may be of advantage depending on the application.

Ke Xu (UNC) was involved in the heterogeneity in biological media working group. Ke graduates in August, 2009 and she worked with Isaac Klapper (Montana State) while he visited SAMSI. She took the SAMSI course MA581 in the fall 2007 on free boundaries and moving interfaces. She spoke in the working group several time about her research and relation with the SAMSI program.

Hui Xie (NCSU) was involved in the interface working group. Hui Xie is a graduate student at NCSU working toward his Ph.D. He took the SAMSI course MA581 in the fall, 2007 on numerical methods for free boundaries and moving interfaces. He presented a talk in the interface working group. His talk was about the finite element method with a locally modified triangulation for the elliptic interface problems.

Qin Zhang (NCSU) was active in two working groups at SAMSI. One is the working group on Interface Problems. He took the SAMSI course MA581 in the fall 2007 on free boundaries and moving interfaces. He is also one of participants of the SAMSI working group on stochastic PDE. He gave a presentation, titled "Optimal Bilinear Control on Quantum Systems," in the SAMSI Postdoc/Graduate Students Seminar. He also presented a talk on the quantum probability theory and quantum filtering problems in the working group. His thesis topic concerns finding a stable feedback solution for quantum control problem arisen in quantum spin systems under continuous measurement which is closed related to the SAMSI program.

6.4 Efforts Made toward Achieving Diversity

There was a significant percentage of women, minority and new faculty throughout the year long program, which can be seen from the list of speakers and participants.

The invited speakers in the Opening Workshop included Lisa Fauci, Karen Daniels and Luci Zhang where the latter two are new faculty. The invited speakers in the Interface Workshop included Sigal Gottlieb and Alina Chertock.

The core participants in the "Waves and Imaging" group meeting included one minority (Daniel Alfaro) and one woman (Yvonne Ou). The "Waves and Imaging" workshop on Jan 31 and Feb 1 featured two women speakers (Margaret Cheney and Liliana Borcea), one minority speaker (Luis Tenorio), and one speaker from industry (Henri Calandra from Total, France). The attendance of the workshop also included a few more minorities, women, and industry researchers.